EFFECT OF TEMPERATURE ON RESISTANCE TO PITTING CORROSION IN DUPLEX STAINLESS STEEL 2205 WELDS

Y. MARTÍNEZ-GALVÁN [1], *L. DZIB-PÉREZ* [2], *M. GARCÍA-RENTERÍA* [2], *O. BILYY* [1], *V. LÓPEZ-MORELOS* [3], *J. GONZALEZ-SANCHEZ* [1]

[1] *Centre for Corrosion Research, Autonomous University of Campeche, Campeche, Mexico;*

[2] *Metallurgy School, Autonomous University of Coahuila, Monclova, Mexico;*

[3] *Metallurgy and Materials Research Institute, Michoacan University of Saint Nicholas of Hidalgo, Morelia, Mexico*

Potentiodynamic polarization was applied to study the electrochemical behaviour of AISI 2205 duplex stainless steel welds and their resistance to pitting corrosion in natural seawater for different temperatures. The gas metal arc welding method (GMAW) was used to manufacture joints with and without the simultaneous application of an external magnetic field of low intensity. The improvement of electrochemical behaviour and resistance to pitting corrosion was evaluated as a function of the electrolyte temperature. The welded joints formed under an external magnetic field of 3 mT presented electrochemical behaviour similar to that for base metal samples, where as joints welded without a magnetic field (0 mT) showed the lowest resistance to pitting corrosion. The joints welded under the external magnetic field presented stable passive behaviour in natural seawater up to the temperature of 45°C, whereas the base metal up to 65°C. The samples welded without a magnetic field showed unstable passive behaviour at a temperature of 25°C. The improvement in the resistance to pitting corrosion of the welds with the application of a magnetic field occurred due to the intensification of austenite phase regeneration during the thermal cycle and the limitation of ferrite phase grains growth. It also limits the precipitation of Cr-rich secondary phases with the consequent reduction of Cr-depleted zones, which ensures the formation of a stable and resistant passive film. The breakdown of this passive film, both in welds with and without a magnetic field, mainly occurs in the heat-affected zone.

Keywords: *duplex stainless steel, pitting corrosion, fusion welding, magnetic field.*

Електрохімічну поведінку зварних з'єднань (ЗЗ) дуплексної нержавної сталі AISI 2205 та її тривкість до пітингової корозії у природній морській воді за різних температур досліджено методом потенціодинамічної поляризації. З'єднання виготовлено дуговим зварюванням у середовищі захисних газів (GMAW) за та без дії зовнішнього низькочастотного магнетного поля (ЗНМП). Електрохімічну поведінку та тривкість до пітингової корозії оцінено як функцію температури електроліту. Виявлено, що ЗЗ, утворене за дії ЗНМП 3 mT, має таку ж електрохімічну поведінку, як і зразки базового металу (БМ), тоді як з'єднання, сформовані без його дії, продемонстрували найнижчу тривкість до пітингової корозії. Поведінка зразка ЗЗ, утвореного за дії ЗНМП, стабільно пасивна у природній морській воді до 45°C, а БМ – до 65°C. Поведінка зразків, зварених без ЗНМП, нестійка пасивна від 25°C. Тривка до пітингової корозії ЗЗ, виконаних із застосуванням ЗНМП, поліпшено внаслідок посилення регенерації аустеніту під час термічного циклу та обмеження росту зерен фериту. Це також перешкоджає осадженню збагачених хромом вторинних фаз із подальшим зменшенням зон, збіднених ним, що сприяє виникненню стабільної та стійкої пасивувальної плівки. Пробій цієї плівки за та без дії ЗНМП відбувався переважно у зоні термічного впливу.

Ключові слова: *дуплексна нержавна сталь, пітингова корозія, зварювання плавленням, магнетне поле.*

Corresponding author: J. GONZALEZ-SANCHEZ, e-mail: jagonzal@uacam.mx

Introduction. The excellent mechanical properties, good machinability, and high corrosion resistance are some of the most important characteristics of duplex stainless steels (DSSs), which make them widely used in oil, chemical, nuclear, and other power generation industries around the world, along with their lower cost compared with Ni-based alloys and super austenitic stainless steels [1–4]. DSSs present superior properties due to their almost 50:50 two-phase ferrite/austenite duplex microstructure, which provides synergistically both the mechanical and electrochemical properties of the two phases.

Modern equipment and engineering structures manufactured with DSSs frequently require welding junctions of different parts. Despite fusion welding is nowadays a controlled and standardized process, DSSs undergo severe microstructure transformations due to the thermal cycles, affecting the phase distribution and balance in the high-temperature heat-affected zone (HAZ) and in the weld metal (WM) [5, 6]. The microstructure evolution and the precipitation of detrimental phases affect the mechanical properties and the resistance to pitting corrosion of DSSs [4, 7–9]. The thermal cycles during fusion welding stimulate the grain growth of the ferrite phase (δ) due to the total or partial dissolution of the austenite phase (γ) in the high-temperature HAZ [4, 5]. Detrimental phases like σ phase, nucleate along the δ/γ interfaces and grow into the δ-phase in the high-temperature HAZ decreasing the toughness and the resistance to pitting corrosion [6–8]. CrN is also an intermetallic phase that decreases the fracture toughness of DSS by precipitating within the δ-phase grains and along the δ–δ and δ–γ boundaries [1, 2, 4–7]. The precipitation of intermetallic phases at temperatures ranging from 600 to 950°C, leads to a considerable loss of toughness that decreases the resistance to fatigue damage due to the limited deformability [8, 9]. To determine the real capabilities of welded DSS structures, when they are in contact with electrolytes at temperatures higher than room temperature, a deep understanding of the relationship between the δ–γ balance, texture, local misorientation and grain morphology with the electrochemical behaviour is mandatory [10–12]. As reported [12], it demonstrated that the application of a magnetic field of 3 mT induced an electromagnetic interaction during the welding of 2205 DSS; this interaction modified the microstructure evolution at the HAZ promoting the increase of austenite regeneration during thermal cycles and avoided the precipitation of detrimental secondary phases.

The present research work focuses on demonstrating the beneficial effect of the application of an external EMF of 3 mT during the gas metal arc welding (GMAW) of 2205 DSS on its resistance to pitting corrosion in natural seawater at temperatures higher than 28°C, which is the annual average temperature of the seawater in the Campeche sea at the Gulf of Mexico.

Experimental. Plates of 2205 DSS (6.35×70×150 mm) with a single *V* groove preparation, were welded using the GMAW process with an ER-2209 electrode of 1.2 mm in diameter 160 mm/s and as shielding gas a mixture of 98% Ar + 2% O_2 (17 l/min). The experimental setup for welding with the application of an external magnetic field is explained in detail elsewhere [12–14]. A magnetic field of 3 mT was applied during welding, and welded joints were made without applying a magnetic field (0 mT). The current 236...248 A and voltage 27.5 V were adjusted to maintain an approximate heat input of 1.4 kJ/mm considering an efficiency of 75%. The preparation of samples for the metallographic and electrochemical analysis consisted of small pieces cut transverse to the direction of the weld bead and machined in a prism with a length of 5 mm, containing the weld bead in the centre. Subsequently, the samples were subjected to a standard metallographic process with SiC paper of different grit up to 1200 and with polishing with diamond paste. To reveal phases and grain boundaries, an electrochemical attack was performed using a 30% HNO_3 solution applying 2 V for periods of 20 s. For the electrochemical tests, the surface of the sample was ground up to 1200 grit.

Potentiodynamic polarization was applied to the welded samples using a conventional three-electrode cell with a calomel electrode as the reference electrode, a graphite bar as a counter electrode and the 2205 DSS welded samples as the working electrodes. The exposed area of the working electrodes containing the HAZ, WM, and base metal (BM) was 1 cm^2, the electrochemical tests were carried out three times using natural seawater at different temperatures (25°C; 30; 35; 45; 55; 60 and 65°C). The electrochemical cell was connected to an electrochemical workstation Solartron, model Z83, PC controlled. The potentiodynamic polarization was carried out by applying a potential ramp starting at a cathodic overpotential of 500 mV vs OCP followed by an anodic overpotential of 1200 mV with a scan rate of 20 mV/min. The electrochemical polarization tests followed the ASTM G48-99a standard, with the electrolyte at the temperatures mentioned above. Because at room temperature it is difficult to establish a pitting potential from potentiodynamic polarization tests for the AISI 2205 DSS in natural seawater, the strategy for this investigation was to evaluate the electrochemical behaviour of the welded samples, with and without applied magnetic field during the GMAW process at temperatures higher than 28°C. The tests at 25°C were conducted to compare with the information from the literature.

After the electrochemical tests, the surface of the welded samples was analyzed by optical microscopy to evaluate the corrosion damage form, distribution, and severity.

Results. Fig. 1 shows the microstructure of the BM, the fusion zone (FZ), and the HAZ of the welded samples manufactured with the simultaneous application of a magnetic field of 3 mT and samples made without the application of magnetic field (0 mT). The BM presented a microstructure constituted of 52% ferrite (δ) and 48% austenite (γ).

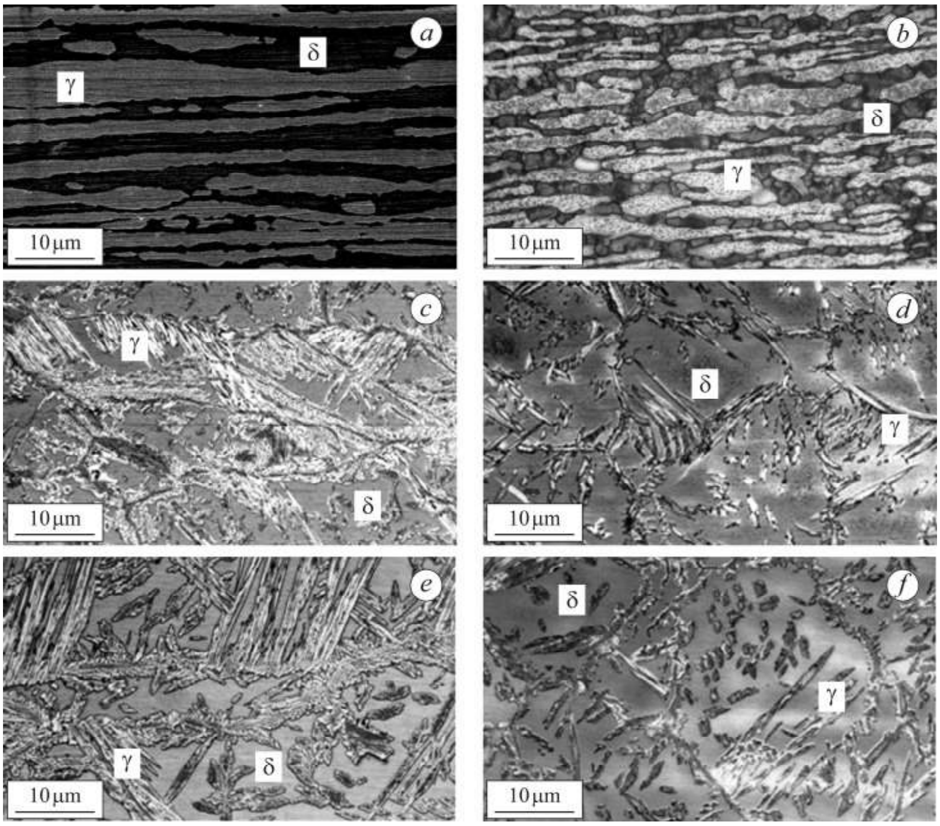


Fig. 1. Microstructure (× 2000) of the BM and welded joints *a* – BM surface area; *b* – BM transverse area; FZ (*c*) and HAZ (*d*) of the welded joints with the application of a magnetic field of 3 mT; FZ (*e*) and HAZ (*f*) of welds made without the application of a magnetic field.

The FZ of both welds, 0 mT, and 3 mT are very similar because the 2209 DSS is filler metal, whereas the HAZ is different for both welded samples. The samples welded under the 3 mT EMF induced one of the smallest HAZ areas and smaller grains at 90 % of the cumulative frequency as compared with welds made without EMF in both the high-temperature HAZ. Also in the welded samples made with a magnetic field of 3 mT, the quantity of the γ phase is higher than in the welds made without a magnetic field. As reported [12, 13], the 3 mT applied magnetic field during the GMAW process induced a higher regeneration of austenite. HAZ is smaller in the welded samples with a magnetic field application than the welds made under 0 mT, which is corroborated in [12, 13] and as shown in Fig. 2.

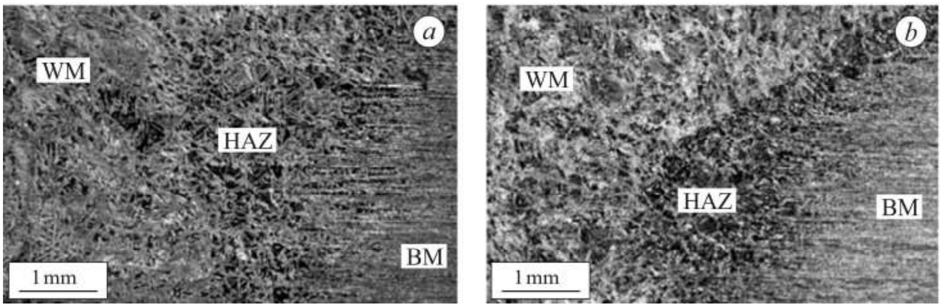
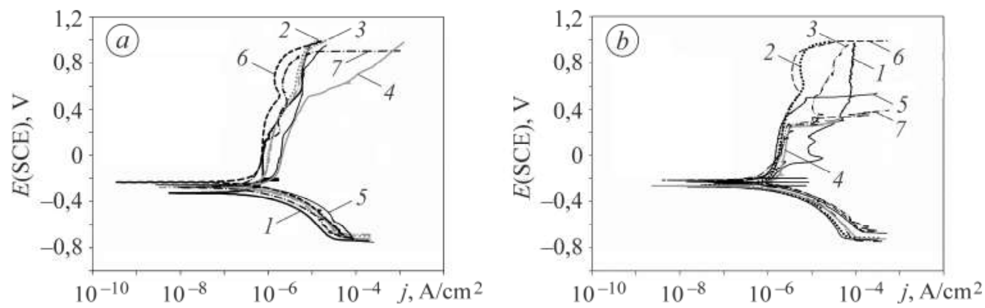


Fig. 2. Micrography of the 2205 DSS welds made without magnetic field (0 mT) (*a*) and under the effect of a magnetic field of 3 mT (*b*) [15].

Fig. 3 shows the electrochemical behaviour of the AISI 2205 DSS samples in the three different metallurgical conditions: BM, conventional welds (0 mT), and welds with a magnetic field of 3 mT from the polarization curves in natural seawater at 25°C; 30; 35; 45; 55; 60 and 65°C. These results clearly show that the BM does not present a pitting potential for polarization at temperatures lower than 65°C in natural seawater. The samples welded conventionally, 0 mT showed an unstable passive condition during the potentiodynamic polarization and pitting corrosion at temperatures higher than 45°C.



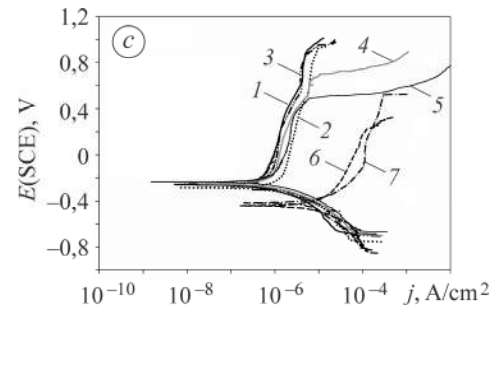


Fig. 3. Polarization curves from the potentiodynamic polarization of samples of BM (*a*); conventional welds (*b*) and welds with a magnetic field of 3 mT (*c*) in natural seawater at: *1* – 25°C; *2* – 30; *3* – 35; *4* – 45; *5* –55; *6* – 60; *7* – 65°C.

As temperature increases the cathodic current density also increases on samples of welds made without the application of a magnetic field, however, the anodic polarization induced unstable behaviour of the passive film. The CPT tests indicate that pitting corrosion is induced when the temperature is around 47°C. Polarization tests at temperatures lower than 45°C showed transpassive dissolution without pitting.

As reported [15, 16] for the case of AISI 2205 DSS welded by GMAW assisted by magnetic fields of several intensities, the critical pitting temperature for the samples welded under a magnetic field of 3 mT was the highest after the one for the BM. In the case of welds made under the influence of the 3 mT magnetic field, the welds show high resistance to pitting corrosion at temperatures lower than 55°C. Even at 45°C the welds presented transpassive dissolution with no pitting corrosion. At 55°C the weld develops pitting corrosion, holding its passive condition up to a potential of 500 mV vs SCE.

The important aspect of this result is that the detrimental effect of heat input during the thermal cycles of fusion welding like the GMAW process can be reduced by the application of an axial magnetic field of low intensity (3 mT). Higher magnetic field intensities applied do not promote better resistance to pitting and intergranular corrosion.

The potentiodynamic polarization of the samples in natural seawater at temperatures higher than 45°C presented a similar cathodic kinetics, however, the anodic behaviour of the welded joints presented a reduction of the potential window for passive condition. The breakdown of the passive layer, both in welding with and without the application of a magnetic field, was formed mainly in the HAZ, due to the microstructural discontinuity that causes the change in the δ/γ phase relationship and the formation of detrimental secondary phases. The WM zone (AE 2209) presented minimum corrosion pits, thus showing that the microstructural composition of this zone after the solidification process presents a high resistance to pitting corrosion on the AISI 2205 DSS welds.

The resistance to pitting corrosion was calculated in terms of the difference

$$\Delta V = E_p - E_{\mathrm{corr}}, \tag{1}$$

where E_p, and E_{corr} are the pitting and corrosion potentials, respectively determined from the potentiodynamic polarization tests at different temperatures. For samples of BM, it is worth mentioning that at temperatures below 65°C this alloy did not present a pitting potential; instead, the evolution of O_2 and H_2 was promoted at high anodic potentials. The table presents this result for BM samples of 2205 DSS and welded samples with and without the application of magnetic field, 3 mT and 0 mT respectively as a function of the temperature of the natural seawater. The empty cells correspond to the tests in which no pitting potential could not be established.

The resistance to pitting corrosion in terms of ΔV (1) from the potentiodynamic polarization of samples of BM, conventional welds, and welds with a magnetic field of 3 mT in natural seawater

Temperature, °C	ΔV, V		
	BM	0 mT	3 mT
25	–	0.50 ± 0.020	–
30	–	0.40 ± 0.028	–
35	–	0.45 ± 0.025	1.2 ± 0.032
45	–	0.44 ± 0.020	0.92 ± 0.018
55	–	0.65 ± 0.030	0.86 ± 0.025
60	–	0.53 ± 0.020	0.91 ± 0.020
65	1.2 ± 0.022	0.51 ± 0.025	1.06 ± 0.022

In all cases, the corrosion pits were formed in the HAZ at different temperatures, no pits were formed at the FZ and the corrosion pits on BM at 65°C were formed at the δ/γ phase boundaries with the pits growing in the ferrite phase. This aspect is one of the most important parameters for the resistance to pitting corrosion of duplex stainless steel welds, along with the quantity and distribution of detrimental secondary phases [17, 18].

CONCLUSIONS

This investigation confirmed the beneficial effect of an applied axial magnetic field during the GMAW joining of AISI 2205 DSS, with the following conclusions. The AISI 2205 DSS did not present pitting corrosion in natural seawater at temperatures lower than 65°C. The application of an axial magnetic field of 3 mT intensity during the GMAW of the AISI 2205 DSS induced higher resistance to pitting corrosion than the samples welded conventionally (0 mT). The samples welded without the application of a magnetic field presented the poorest resistance to pitting corrosion in natural seawater at all temperatures evaluated. Even with the beneficial effect of the applied magnetic field, pitting corrosion takes place in natural seawater at the HAZ at temperatures equal to or higher than 65°C, the BM presents also pitting corrosion under this experimental condition.

1. *Nilsson J.-O.* Super duplex stainless steels // Mat. Sci. and Techn. (United Kingdom). – 1992. – **8**, № 8. – P. 685–700. DOI:10.1179/mst.1992.8.8.685
2. *Charles J.* Duplex stainless steels, a review after DSS'07 held in grado // Revue De Metallurgie. Cahiers D'Informations Techniques. – 2008. – **105**, № 3. – P. 155–171. DOI:10.1051/metal:2008028
3. *Duplex* Stainless Steels: Microstructure Properties and Applications / Ed. by R. N. Gunn. – Cambridge, England: Woodhead Publ., 1997. – 216 p.
4. *Duplex* Stainless Steels / Eds.: by I. Alvarez-Armas, S. Degallaix-Moreuil. – New Jersey: ISTE Ltd and John Wiley & Sons, Inc., 2009. – 464 p.
5. *Pouranvari M., Khorramifar M., and Marashi S. P. H.* Ferritic-austenitic stainless steels dissimilar resistance spot welds: Metallurgical and failure characteristics // Sci. and Techn. of Weld. and Join. – 2016. – **21**, № 6. – P. 438–445. DOI:10.1080/13621718.2015.1124491
6. *Varol I., Baeslack W. A., and Lippold J. C.* Characterization of weld solidification cracking in a duplex stainless steel // Mat. Characterization. – 1997. – **39**, № 2–5. – P. 555–573. DOI:10.1016/s1044-5803(97)00144-7
7. *Solomon H. D.* Age hardening in a duplex stainless steel // J. Heat. Treating. – 1983. – **3**, № 1. – P. 3–15. DOI:10.1007/BF02833149
8. *Pohl M., Storz O., and Glogowski T.* Effect of intermetallic precipitation on the properties of duplex stainless steel // Mat. Characterization. – 2007. – **58**, № 1. – P. 65–71. DOI:10.1016/j.matchar.2006.03.015
9. *Michalska J. and Sozańska M.* Qualitative and quantitative analysis of σ and χ phases in 2205 duplex stainless steel // Mat. Characterization. – 2006. – **56**, Sp. Is. 4–5. – P. 355–362. DOI:10.1016/j.matchar.2005.11.003
10. *Effect* of the heat treatment on the corrosion resistance of duplex stainless steels / L. Pezzato, M. Lago, K. Brunelli, M. Breda, and I. Calliari // J. of Mat. Eng. and Performance. – 2018. – **27**, № 8. – P. 3859–3868. DOI:10.1007/s11665-018-3408-5
11. *Correlation* between critical pitting temperature and degree of sensitisation on alloy 2205 duplex stainless steel / N. Ebrahimi, M. Momeni, M. H. Moayed, and A. Davoodi // Corr. Sci. – 2011. – **53**, № 2. – P. 637–644. DOI:10.1016/j.corsci.2010.10.009
12. *Improvement* of localized corrosion resistance of AISI 2205 duplex stainless steel joints made by gas metal arc welding under electromagnetic interaction of low intensity / M.-A. García-Rentera, V.-H. López-Morelos, R. Garcia-Hernandez, L. Dzib-Pérez, E. M. García-Ochoa, and J. González-Sánchez // Appl. Surf. Sci. – 2014. – **321**. – P. 252–260. DOI:10.1016/j.apsusc.2014.10.024

13. *Effect* of electromagnetic interaction during fusion welding of AISI 2205 duplex stainless steel on the corrosion resistance / M. A. García-Rentería, V. H. López-Morelos, J. González-Sánchez, R. García-Hernández, L. Dzib-Pérez, and F. F. Curiel-López // Appl. Surf. Sci. – 2017. – **396**. – P. 1187–1200. DOI:10.1016/j.apsusc.2016.11.109

14. *Effect* of magnetic field applied during gas metal arc welding on the resistance to localised corrosion of the heat affected zone in AISI 304 stainless steel / F. F. Curiel, R. García, V. H. López, and J. González-Sánchez // Corr. Sci. – 2011. – **53**, № 7. – P. 2393–2399. DOI:10.1016/j.corsci.2011.03.022

15. *García-Rentería M., López-Morelos V., and García-Hernández R.* Effect of low-intensity electromagnetic interaction on the microstructure and mechanical properties of stainless steel duplex welds // Ingenius. – 2014. – № 2 (2008). – P. 40–45. DOI.org/10.17163/ings.n12.2014.05

16. *Effect* of a magnetic field applied during fusion welding on the fatigue damage of 2205 duplex stainless steel joints / J. Rosado-Carrasco, U. Krupp, V. H. López-Morelos, A. Giertler, M. A. García-Rentería, and J. González-Sánchez // Int. J. of Fatig. – 2019. – **121**. – P. 243–251. DOI:10.1016/j.ijfatigue.2018.12.022.

17. *Mosallaee M. and Babanejhad A.* Correlation between microstructure and pitting corrosion behavior of TLP bonded DSS-2205/Ni–P/DSS-2205 specimens // Metals and Mat. Int. – 2021. – **27**, № 8. – P. 2837–2847. DOI:10.1007/s12540-020-00625-9

18. *Welding* behaviour of duplex stainless steel AISI 2205: A Review / A. N. Chaudhari, K. Dixit, G. S. Bhatia, B. Singh, P. Singhal, and K. K. Saxena // Mat. Today: Proc. – 2019. – **18**. – P. 2731–2737. DOI:10.1016/j.matpr.2019.07.136

Received 01.08.2022