Metal welding green corrosion inhibitor: A review

Surianto,[1] M. Rihotimawati,[1] H. Basri,[1] Alimuddin,[1] A. Wahyudianto[1]* and A. Fernandes[2]**

[1]Politeknik Negeri Samarinda, Jl. DR Ciptomangunkusumo, Kampus Gunung Lipan, Samarinda, East Kalimantan, Indonesia

[2]Research Center for Biomass and Bioproducts, National Research and Innovation Agency, Jl. Raya Jakarta – Bogor Km. 46, Cibinong, Kab. Bogor, West Java, 16911, Indonesia

*E-mail: *arif.wahyudianto@polnes.ac.id, **af.andrian.fernandes@gmail.com*

Abstract

Welding has been a fundamental tool in the evolution of metallurgy, to combine metal components to construct structures, cars, machinery, and other products in industries. Welded metal can corrode for a variety of reasons, therefore preventing corrosion and determining the fundamental reasons are critical to resolving the issue. Corrosion of welded metal must be prevented by various methods, including the application of natural corrosion inhibitors. Corrosion inhibitors are compounds that are used during the welding process to reduce the effects of corrosion on metal surfaces. Plants extract-based corrosion inhibitors can help prolong the service life of welded metal structures and components in metal welding procedures. The plant extracts indicated below have demonstrated potential as metal welding corrosion inhibitors. Neem (*Azadirachta indica*) extract, aloe vera extract, and rambutan fruit peel extract have all shown promise as corrosion inhibitors in metal welding. Oleochemicals can be used as corrosion inhibitors in metal welding as bio-based coatings. *iso*-Undecenoic and *iso*-undecanoic acid based polyol esters can be utilized as corrosion inhibitors during metal welding. Oleochemical-based corrosion inhibitors are frequently preferred over traditional petroleum-based inhibitors due to their lower environmental impact. Oleochemical corrosion inhibitors are generally compatible with a wide range of metals. The review highlights the importance of corrosion prevention in metal welding and discusses the potential of plant extracts and oleochemicals as effective corrosion inhibitors.

Received: May 20, 2024 Published: June 12, 2024 doi: 10.17675/2305-6894-2024-13-2-31

Keywords: *metal welding, corrosion, inhibitors, plant extracts, oleochemical.*

1. Introduction

Welding has been a fundamental tool in the evolution of metallurgy, allowing for the fabrication of complicated shapes and strong structures [1]. The capacity to combine metals in diverse combinations has transformed industries ranging from construction to automotive, aircraft, and beyond.

Forge welding was an ancient procedure in which metal pieces were heated and then hammered together to make a weld [2]. This procedure was employed in blacksmithing for the manufacture of tools and weapons. Aside from that, prior to the contemporary welding procedures, metal was generally joined with rivets or bolts [3], which limited design flexibility [4] and increased weight [5]. Welding technology advanced significantly throughout the twentieth century, enabling for more complicated shapes and stronger joints. Metal welding creates a variety of corrosion throughout usage, necessitating the development of diverse corrosion treatment procedures, in particular, those based on natural inhibitors.

2. The Metal Needs to be Welded

Metal welding is necessary to combine metal components to produce structures, vehicles [6], machines [7], and other items in industries including shipbuilding, automotive, aerospace, and construction. Metal welding may be necessary to fix damage to metal components [8] and structures [9] resulting from wear and tear, corrosion, or mishaps. This can entail repairing fractures, strengthening weak areas, or swapping out damaged pieces.

Figure 1. Welded motorbike exhaust joints that are corroded.

Metal components or structures can be made to order using welding to satisfy certain specifications [10]. This might entail changing the size, providing features, or incorporating extra components. Buildings, bridges, pipelines, and other infrastructure projects that require secure joining of metal components to endure a variety of loads [11] and climatic conditions [12] are constructed with the help of welding.

Metal welding is widely used in industry [13] and commerce [14] for jobs including building storage tanks, producing equipment, assembling machinery, and installing structural components. Metal welding is widely utilized in the automotive [15] and transportation [16] sectors to manufacture automobiles, trailers, railcars, and airplanes as well as to repair and modify already existing components. The underwater laser welding/cladding technology is a promising and advanced approach that might be widely used in the repair of damaged equipment [17]. FSW (friction stir welding) is increasingly used in aerospace applications to weld structures comprised of high-strength aluminium alloys, such as large-volume fuel tanks and various components of business jet aircraft [18].

The construction and upkeep of oil refineries, power plants, and other energy facilities depend heavily on welding [19]. Boilers, pressure vessels, pipelines, and other essential parts are built using it. Moreover, welding is a common technique used to create metal artwork and sculptures. Metal components are shaped and joined by artists using welding to fulfil their artistic vision [20].

3. Corrosion of Welded Metal

Welded metal can corrode for several reasons, thus preventing corrosion and identifying its underlying causes are essential to solve the problem. The following are some explanations for why welded metal may be prone to corrosion: welding procedure, the base metal welding, welding filler material, heat affected zone (HAZ), and others.

Some welding procedures, such as arc welding, can create heat-affected zones [21] and change the base metal's metallurgical characteristics [22], which may increase its susceptibility to corrosion. When chromium carbide precipitates at grain boundaries in some metals and alloys, especially stainless steels, certain welding procedures can cause intergranular corrosion to arise [23]. Metal arc welding produces a heat-affected zone with micro-sized corrosion pits [24]. 409M ferritic stainless steel welded by GMAW (gas metal arc welding) has a corrosion rate of 0.4316-0.5285 mpy in 3.5% NaCl solution [25]. Austenitic 304L stainless steel welded with a laser beam produces a reduced heat-affected zone and has a corrosion rate of 0.09732 in/year (inches per year) in ferric chloride solution [26].

Table 1. The percentage of different phases in the weld line of specimens with different weld heat input [24].

Secondary phase, %	Acicular ferrite, %	Widmanestatten ferrite, %	Polygonal ferrite, %	Grain boundary ferrite, %	Specimen
8	60	17	17	11	X42–X42 WH = 0.61 kJ/mm
6	34	11	26	15	X42–X42 WH = 0.68 kJ/mm
5	31	4	30	17	X42–X42 WH = 0.74 kJ/mm

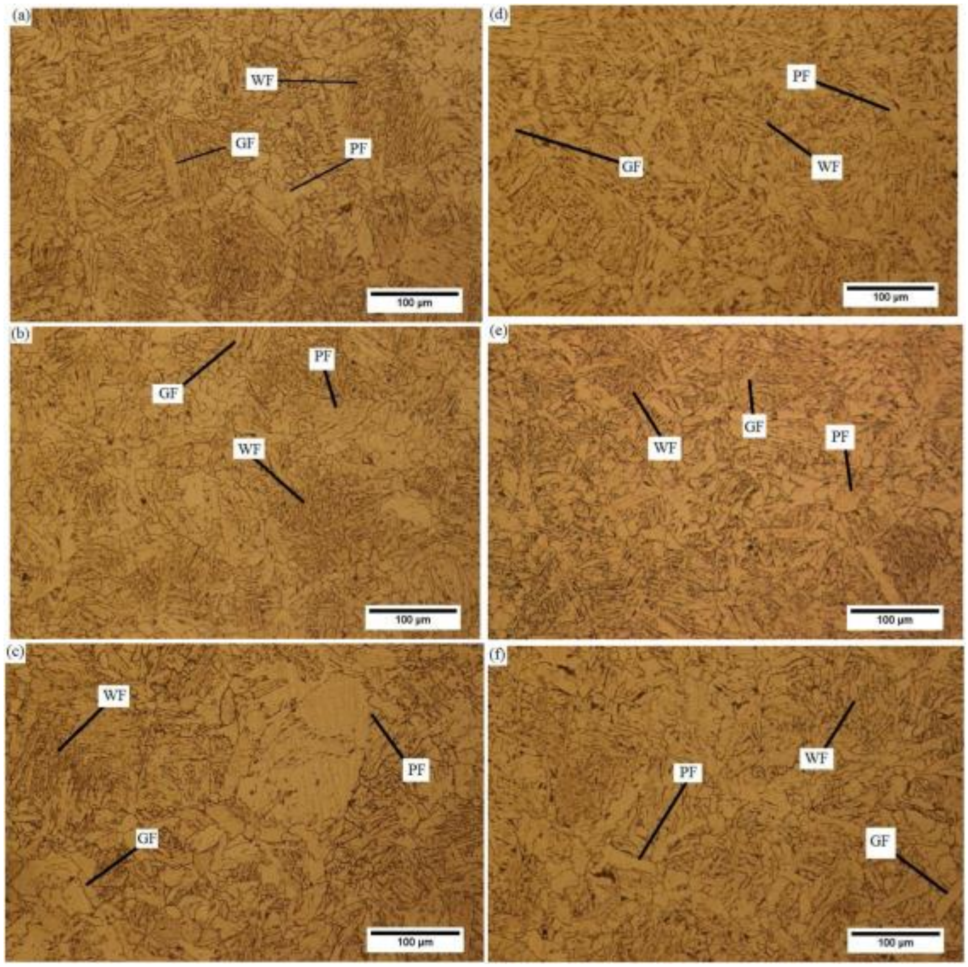

Figure 2. Microstructure of the HAZ for specimens welded with different weld heat inputs: (a) X-42 and 0.61 kJ/mm; (b). X-42 and 0.68 kJ/mm; (c) X-42 and 0.74 kJ/mm; (d) grade B and 0.61 kJ/mm; (e) grade B and 0.68 kJ/mm; (f) grade B and 0.74 kJ/mm. GF stands for grain boundary ferrite, WF stands for Widmanstatten ferrite and PF stands for polygonal ferrite [24].

The corrosion resistance of various metals and alloys varies. The key to preventing corrosion is to select the right base metal for the particular use [27] and environment [28]. The corrosion resistance of the base metal may not always be matched by the filler material used in welding. This problem can be lessened by choosing filler materials that are compatible with each other and have sufficient resistance to corrosion [29]. S201 is a pure copper filler material that may be used for incompatible welding metals such as titanium and copper utilising the gas tungsten arc welding (GTAW) method, which produces improved plasticity and tensile strength [30].

The welding process can alter the microstructure and characteristics of the region immediately surrounding the weld, which could make it more susceptible to corrosion. The process of welding has the potential to leave residual stresses in the welded metal [31], which could facilitate the initiation and spread of corrosion, particularly in regions where stress concentration is present [32]. Inadequate surface preparation prior to welding, such as insufficient removal of impurities, rust, or scale, can weaken the weld's integrity [33] and make it more susceptible to corrosion [34].

4. Prevention of Welded Metal Corrosion

Several preventive actions can be performed to reduce or eliminate welded metal corrosion, such as: appropriate material selection, correct welding technique, post-weld treatment, and frequent inspection and maintenance.

Based on the desired use and environment, select base metals [35] and filler materials [36] with the appropriate corrosion resistance. Adding 1% nickel filler to welded carbon steel pipes reduces corrosion by up to 0.1 mpy and extends their lifespan to 30 years [37]. The AA6082 and AA5052 aluminium alloy specimens made with 95% Mg and 5% Cr filler show a lower corrosion rate (0.012275 mm/y) than the same metal combination that is friction stir welded without filler materials (0.072319 mm/y) [38].

A correct welding technique using the proper welding procedures and parameters can reduce heat input [39] and preserve the integrity of the welded joint [40]. 12Cr2Mo1R low carbon steel and S30408 stainless steel were joined using arc-assisted tungsten insert gas (AA-TIG) backing welding and submerged arc welding (SAW) to fill the cutout [41]. Tensile strength was enhanced up to 1200 rpm of tool rotation and 45 mm/min of welding speed in FSW (friction stir welding) of aluminium alloys AA7075 and AA2014, to reduce heat and corrosion rates in the welding zone [42].

Post-weld treatment can improve the welded metal's resistance to corrosion, such as high-entropy alloy (HEA) coating [43], pickling in acid media [44], or recrystallized metal surface passivation [45]. API 5LX-52 arc steel welded joints passivated with molybdate and submerged in a 3.5% NaCl solution have a corrosion rate of 0.096 MPY [46]. PWHT (post-weld heat treatment) effectively reduced intergranular corrosion in ENiCrFe-7 weld overlay cladding materials after 615°C/48 h [47].

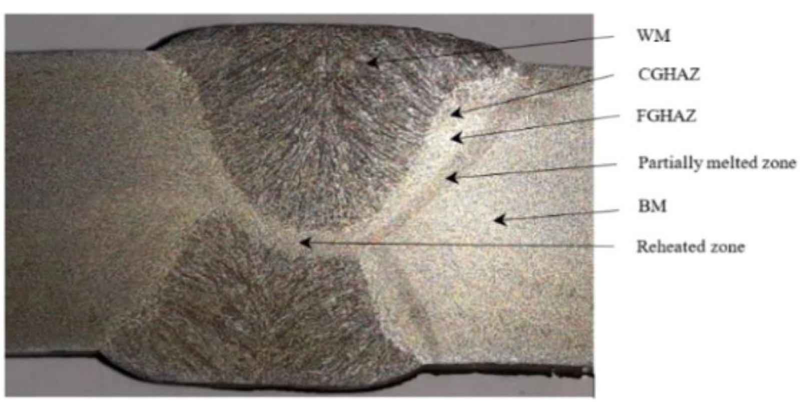

Figure 3. The macromorphology of welded X-52 steel pipeline [46].

Table 2. Electrochemical kinetic parameters of X-52 steel in a 3.5% NaCl solution with different inhibitor concentrations [46].

Regions	Inhibitor concentration, %	E_{corr}, mV_{SCE}	i_{corr}, $\mu A/cm^2$	*CR*, mmpy	*IE*%
Base metal	0	−590.40	25.26	0.142	0
	0.1	−527.58	9.225	0.058	63.48
	0.2	−426.71	0.918	0.005	96.37
	0.3	−427.76	0.345	0.002	98.63
	0.4	−387.41	0.273	0.002	98.92
HAZ	0	−634.88	96.91	0.535	0
	0.1	−459.19	24.81	0.140	74.40
	0.2	−486.48	21.36	0.120	77.97
	0.3	−454.39	1.16	0.007	98.81
	0.4	−396.75	0.851	0.005	99.12
Weld metal	0	−627.52	16.77	0.096	0
	0.1	−527.58	9.23	0.058	44.97
	0.2	−420.97	0.980	0.006	94.15
	0.3	−445.94	0.662	0.004	96.05
	0.4	−373.07	0.170	0.001	98.99

Surface preparation guarantees correct fusion and eliminates impurities, by thoroughly cleaning and preparing the surfaces to be welded [48]. A superhydrophobic Cu-Co coating was successfully applied to the surface of copper-nickel (Cu-Ni) B10 alloy welded joints via electrodeposition, resulting in exceptional thermal stability, self-cleaning, and a reduction in corrosion rate from 0.95651 to 0.00610 mpy [49].

The welded metal can be protected from the corrosive environment by applying coatings [50] or corrosion inhibitors [51]. An inhibition efficacy of up to 91.7% was observed in a study of imidazole as a corrosion inhibitor in carbon steel welding in an alkaline district heating system [52].

To stop further degradation, welded components have to be periodically checked for corrosion [53] and maintenance procedures should be carried out as necessary [54]. It is feasible to reduce the risk of corrosion and guarantee the durability and dependability of welded structures and components by being aware of the elements that lead to corrosion in welded metal and putting the proper preventive measures in place.

5. Plant Extracts as Metal Welding Corrosion Inhibitors

The potential of plant extracts as corrosion inhibitors in metal welding processes has been investigated. Many organic chemicals found in plant extracts, including flavonoids, phenols, alkaloids, tannins, and organic acids, have the ability to suppress corrosion [55]. The following plant extracts have demonstrated potential as metal welding corrosion inhibitors: Neem (*Azadirachta indica*) Extract, Aloe Vera Extract, and rambutan fruit peel extract.

Neem (*Azadirachta indica*) extract contains azadirachtin, nimbin, and nimbidin, which significantly reduce corrosion [56]. Azadirachtin produces a thin layer on metal surfaces, shielding them from corrosion reactions [57]. Nimbin can prevent corrosion-induced fractures in metal surfaces [58]. Aloe vera extract has organic components that have been studied for their ability to suppress corrosion, such as polysaccharides, phenolics, and organic acids [59]. Rambutan (*Nephelium lappaceum* L.) fruit peel extract, which is rich in phenolic compound [60], has been used as a natural inhibitor in welded carbon steel. Its inhibitory efficiency can reach 83% in 3.5% NaCl [61] and 97% in 1 M HCl [62].

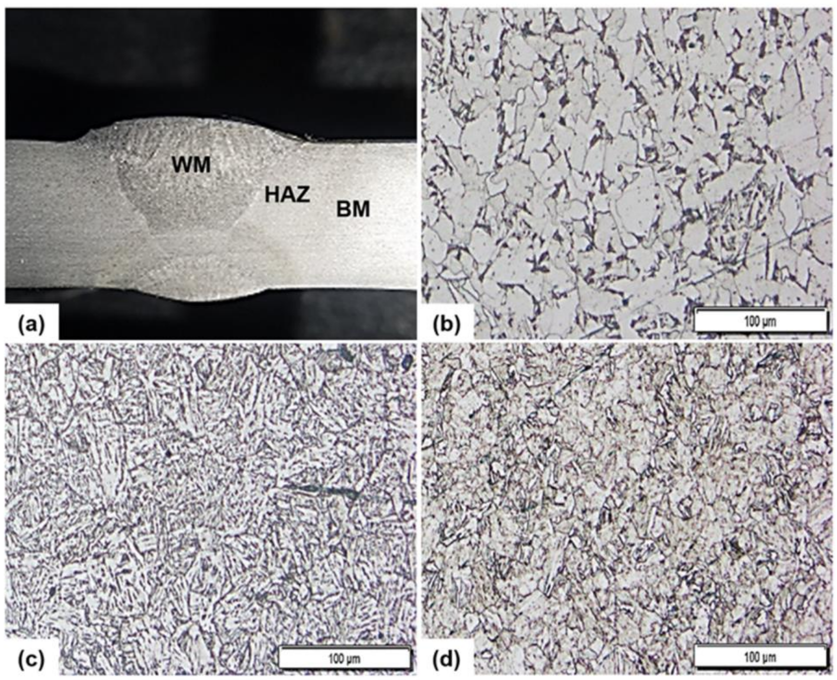

Figure 4. (a) Macrograph of welded samples, (b) weld metal (WM), (c) heat-affected zone (HAZ), (d) base metal (BM) [62].

Table 3. Corrosion parameters calculated by using Tafel extrapolation [62].

NP Extract, g/L	β_a, V/dec	$-\beta_c$, V/dec	E_{corr}, V	i_{corr}, A/cm^2	Corrosion rate, mm/year	*IE*%
			WM			
0	0.096	0.111	−0.414	$1.64 \cdot 10^{-3}$	19.3	0
1	0.101	0.105	−0.438	$1.81 \cdot 10^{-4}$	2.13	89
2	0.081	0.081	−0.442	$9.10 \cdot 10^{-5}$	1.07	94
3	0.075	0.066	−0.437	$8.06 \cdot 10^{-5}$	0.95	95

NP Extract, g/L	β_a, V/dec	$-\beta_c$, V/dec	E_{corr}, V	i_{corr}, A/cm^2	Corrosion rate, mm/year	*IE*%
4	0.068	0.052	−0.439	$6.52\cdot10^{-5}$	0.77	96
5	0.094	0.079	−0.438	$5.72\cdot10^{-5}$	0.67	97
6	0.137	0.101	−0.434	$1.41\cdot10^{-4}$	1.66	91
			HAZ			
0	0.204	0.143	−0.450	$3.41\cdot10^{-4}$	4.01	0
1	0.105	0.102	−0.441	$2.49\cdot10^{-4}$	2.93	27
2	0.117	0.085	−0.440	$2.04\cdot10^{-4}$	2.40	40
3	0.096	0.071	−0.436	$8.23\cdot10^{-4}$	0.97	76
4	0.084	0.076	−0.447	$7.54\cdot10^{-4}$	0.89	78
5	0.086	0.058	−0.436	$6.69\cdot10^{-4}$	0.78	80
6	0.097	0.076	−0.440	$7.49\cdot10^{-4}$	0.88	78
			BM			
0	0.126	0.145	−0.432	$3.46\cdot10^{-4}$	4.08	0
1	0.120	0.118	−0.427	$2.38\cdot10^{-4}$	2.80	31
2	0.132	0.098	−0.432	$2.07\cdot10^{-4}$	2.43	40
3	0.140	0.067	−0.421	$1.57\cdot10^{-4}$	1.85	56
4	0.091	0.065	−0.430	$1.04\cdot10^{-4}$	1.23	70
5	0.112	0.077	−0.427	$1.2\cdot10^{-4}$	1.40	65
6	0.103	0.078	−0.422	$1.2\cdot10^{-4}$	1.41	65

Plant extracts have the potential to be applied in multiple forms, including coatings on metal surfaces, aqueous solutions, and organic solvent solutions. They work by covering the metal surface with a protective layer that prevents corrosive environmental attacks [63].

Plant extract-based corrosion inhibitors can help prolong the service life of welded metal structures and components in metal welding procedures [64], where corrosion can be a major concern due to the exposure of metal surfaces to severe environments. Nevertheless, to ascertain whether these inhibitors are effective and compatible with certain metal alloys and welding procedures, extensive testing and assessment must be done. For the intended corrosion protection, these inhibitors' concentrations and application techniques must also be optimised.

6. Oleochemicals as Metal Welding Corrosion Inhibitors

Oleochemicals can be used to reduce corrosion during metal welding procedures [65]. Corrosion inhibitors are compounds that are used during the welding process to reduce the effects of corrosion on metal surfaces. They provide a protective layer on the metal surface, preventing it from contacting corrosive elements.

Oleochemicals can be used as corrosion inhibitors in metal welding as bio-based coatings [66], lubricants and anti-spatter agents, and rust inhibitors. Oleochemicals can be combined to create bio-based coatings that are applied to metal surfaces prior to or following welding [67]. Valeric acid and stearic acid are ionic liquids that penetrate the microcracks generated at a freshly sliced surface and hinder re-welding [68]. These coatings can provide a protective barrier against corrosive substances, reducing rust and metal corrosion.

Certain oleochemicals, such as vegetable oils and derivatives, can be employed as lubricants and anti-spatter agents during the welding process [69]. Vegetable oil can be used as a lubricant for welded metal ends [70], lowering the welding temperatures [71] and lowering the possibility of rust on the metal. They contribute to the metal's integrity and lower the danger of corrosion by minimizing friction and preventing spatter from adhering to the surface.

Some oleochemicals contain components that suppress rust [72]. *iso*-Undecenoic and *iso*-undecanoic acid-based polyol esters can be utilised as corrosion inhibitors during metal welding [73]. These compounds can be used in welding fluxes or directly on metal surfaces to prevent rust and corrosion.

Oleochemical-based corrosion inhibitors are frequently preferred over traditional petroleum-based inhibitors due to their lower environmental impact [74]. They are generated from renewable plant sources and are biodegradable, making them a more environmentally friendly solution for corrosion protection in welding. Palm oil fatty acids contain ester and hydroxyl groups that can be converted into environmentally beneficial welded metal coatings [75].

Oleochemical corrosion inhibitors are generally compatible with a wide range of metals [76] and welding processes [77], making them useful solutions for corrosion protection in a variety of welding applications. Natural garlic oil, at 1% by weight, can improve metal welding's corrosion-prevention efficacy [78].

Conclusion

Welded metal can corrode due to various reasons, including welding procedures, base metal welding, welding filler material, Heat Affected Zone (HAZ), and others. Some welding procedures can change the base metal's metallurgical characteristics, making it more susceptible to corrosion. Preventive measures can be taken to reduce or eliminate welded metal corrosion, such as appropriate material selection, correct welding technique, post-weld treatment, and frequent inspection and maintenance. These measures can improve the welded metal's resistance to corrosion and ensure the durability and reliability of welded structures and components.

The potential of plant extracts as corrosion inhibitors in metal welding processes has been investigated. Neem (*Azadirachta indica*) extract, Aloe Vera Extract, and rambutan fruit peel extract have demonstrated potential as metal welding corrosion inhibitors. Plant extract-based corrosion inhibitors can help prolong the service life of welded metal structures and components in metal welding procedures. Oleochemicals can be used as corrosion inhibitors in metal welding as bio-based coatings, lubricants and anti-spatter agents, and rust inhibitors. They provide a protective barrier against corrosive substances, reducing rust and metal corrosion. Oleochemical-based corrosion inhibitors are frequently preferred over traditional petroleum-based inhibitors due to their lower environmental impact. They are compatible with a wide range of metals and welding processes, making them useful solutions for corrosion protection in various welding applications.

References

1. A. Heidarzadeh, S. Mironov, R. Kaibyshev, G. Çam, A. Simar, A. Gerlich, F. Khodabakhshi, A. Mostafaei, D.P. Field, J.D. Robson, A. Deschamps and P.J. Withers, Friction Stir Welding/Processing of Metals and Alloys: A Comprehensive Review on Microstructural Evolution, *Prog. Mater. Sci.*, 2021, **117**, 100752. doi: 10.1016/j.pmatsci.2020.100752
2. E.J. France, The Nature of Welding and Its Relationship with the Steel Industry, *Steel Times Int.*, 2020, **44**, 22–27.
3. A. Galińska, Mechanical Joining of Fibre Reinforced Polymer Composites to Metals – a Review. Part i: Bolted Joining, *Polymers*, 2020, **12**, 2252. doi: 10.3390/polym12102252
4. J. Wu, C. Chen, Y. Ouyang, D. Qin and H. Li, Recent Development of the Novel Riveting Processes, *Int. J. Adv. Manuf. Technol.*, 2021, **117**, 19–47. doi: 10.1007/s00170-021-07689-w
5. F. Lambiase, S.I. Scipioni, C.J. Lee, D.C. Ko and F. Liu, A State-of-the-Art Review on Advanced Joining Processes for Metal-Composite and Metal-Polymer Hybrid Structures, *Materials*, 2021, **14**, 1890. doi: 10.3390/ma14081890
6. M.A. Karim and Y.-D. Park, A Review on Welding of Dissimilar Metals in Car Body Manufacturing, *Journal of Welding and Joining*, 2020, **38**, 8–23. doi: 10.5781/jwj.2020.38.1.1
7. B .Wang, S.J. Hu, L. Sun and T. Freiheit, Intelligent Welding System Technologies: State-of-the-Art Review and Perspectives, *Journal of Manufacturing Systems*, 2020, **56**, 373–391. doi: 10.1016/j.jmsy.2020.06.020
8. D. Tanasković, S. Petrović, B. Đorđević, A. Matavž and T. Mijatović, Algorithm for Defining Quality of Base Material for Repair Welding, *Struct. Integr. Life*, 2020, **21**, 279–284.

9. D. Stroianovskyi, The Study of Welding Requirements during Construction and Installation of Seismic-Resistant Steel Structures, *Journal of Research in Science, Engineering and Technology*, 2020, **8**, 17–20. doi: 10.24200/jrset.vol8iss2pp17-20
10. H.M.H.K. Herath, D.S. Jayaweerarathne, R.S.S.A. Wijesundara and K.K. Wijesundara, Performance-Based Design Method for Bolted Stiffened End-Plate Connection under Monotonic Loading, *Structures*, 2023, **53**, 214–227. doi: 10.1016/j.istruc.2023.04.088
11. H. Rajanayagam, K. Poologanathan, P. Gatheeshgar, G.E. Varelis, P. Sherlock, B. Nagaratnam and P.Hackney, A-State-Of-The-Art Review on Modular Building Connections, *Structures*, 2021, **34**, 1903–1922. doi: 10.1016/j.istruc.2021.08.114
12. M.M. Yehia, S.M. Gaawan, R. Elwan, O.R. Shahin and W.Z. El-sayad, Structural Performance Evaluation of Cold Formed Steel Cantilever Beams with Varying Perforation Patterns, *Alexandria Eng. J.*, 2024, **91**, 204–221. doi: 10.1016/j.aej.2024.01.049
13. Y.M. Zhang, Y.P. Yang, W. Zhang and S.J. Na, Advanced Welding Manufacturing: A Brief Analysis and Review of Challenges and Solutions, *J. Manuf. Sci. Eng. Trans.*, 2020, **142**, 110816. doi: 10.1115/1.4047947
14. K.R. Madavi, B.F. Jogi and G.S. Lohar, Metal Inert Gas (MIG) Welding Process: A Study of Effect of Welding Parameters, *Mater. Today Proc.*, 2022, **51**, 690–698. doi: 10.1016/j.matpr.2021.06.206
15. C. Khalil, S. Marya and G. Racineux, Magnetic Pulse Welding and Spot Welding with Improved Coil Effciency-Application for DissimilarWelding of Automotive Metal Alloys, *J. Manuf. Mater. Process.*, 2020, **4**, 69. doi: 10.3390/jmmp4030069
16. R.D. Ardika, T. Triyono and N. Muhayat, Triyono A Review Porosity in Aluminum Welding, *Procedia Structural Integrity*, 2021, **33**, 171–180. doi: 10.1016/j.prostr.2021.10.021
17. G. Sun, Z. Wang, Y. Lu, M. Chen, K. Yang and Z. Ni, Underwater Laser Welding/Cladding for High-Performance Repair of Marine Metal Materials: A Review, *Chinese J. Mech. Eng. (Engl. Ed.)*, 2022, **35**, 5. doi: 10.1186/s10033-021-00674-0
18. M.M.Z. Ahmed, M.M. El-Sayed Seleman, D. Fydrych and G. Çam, Friction Stir Welding of Aluminum in the Aerospace Industry: The Current Progress and State-of-the-Art Review, *Materials*, 2023, **16**, 2971. doi: 10.3390/ma16082971
19. A. Asuega, B.J. Limb and J.C. Quinn, Techno-Economic Analysis of Advanced Small Modular Nuclear Reactors, *Appl. Energy*, 2023, **334**, 120669. doi: 10.1016/j.apenergy.2023.120669
20. N. Li, Metal Jewelry Craft Design Based on Computer Vision, *Computational Intelligence and Neuroscience*, 2022, **2022**, 3843421. doi: 10.1155/2022/3843421
21. S. Sinhmar and D.K. Dwivedi, Art of Friction Stir Welding to Produce Weld Joint without Rotation of Shoulder with Narrow Heat-Affected Zone and High Corrosion Resistance, *Sci. Technol. Weld. Joining*, 2020, **25**, 490–495. doi: 10.1080/13621718.2020.1746512

22. B. Yelamasetti, T.V. Vardhan and G.V. Ramana, Study of Metallurgical Changes and Mechanical Properties of Dissimilar Weldments Developed by Interpulse Current TIG Welding Technique, *Proc. Inst. Mech. Eng. Part C*, 2021, **235**, 2985–2997. doi: 10.1177/0954406220960780
23. H. Yan, Z. He, L. Nan, C. Wei, T. Xu and J. Liu, Effects of Cooling Rate on the Precipitation Behavior of Grain Boundary Carbide and Corrosion Resistance of 5Cr15MoV Stainless Steel, *Mater. Corros*., 2020, **71**, 1257–1265. doi: 10.1002/maco.202011505
24. R. Ashari, A. Eslami, M. Shamanian and S. Asghari, Effect of Weld Heat Input on Corrosion of Dissimilar Welded Pipeline Steels under Simulated Coating Disbondment Protected by Cathodic Protection, *J. Mater. Res. Technol*., 2020, **9**, 2136–2145. doi: 10.1016/j.jmrt.2019.12.044
25. S.P. Ambade, A. Sharma, A.P. Patil and Y.M. Puri, Effect of Welding Processes and Heat Input on Corrosion Behaviour of Ferritic Stainless Steel 409M, *Mater. Today Proc*., 2019, **41**, 1018–1023. doi: 10.1016/j.matpr.2020.06.251
26. A. Gnanarathinam, D. Palanisamy, N. Manikandan, A. Devaraju and D. Arulkirubakaran, Comparison of Corrosion Behavior on Laser Welded Austenitic Stainless Steel, *Mater. Today Proc*., 2021, **39**, 649–653, doi: 10.1016/j.matpr.2020.09.184
27. R. Bender, D. Féron, D. Mills, S. Ritter, R. Bäßler, D. Bettge, I. De Graeve, A. Dugstad, S. Grassini, T. Hack M. Halama, En-H. Han, T. Harder, G. Hinds, J. Kittel, R. Krieg, C. Leygraf, L. Martinelli, A. Mol, D. Neff, J.-O. Nilsson, I. Odnevall, S. Paterson, S. Paul, T. Prošek, M. Raupach, R.I. Revilla, F. Ropital, H. Schweigart, E. Szala, H. Terryn, J. Tidblad, S. Virtanen, P. Volovitch, D. Watkinson, M. Wilms, G. Winning and M. Zheludkevich, Corrosion Challenges towards a Sustainable Society, *Mater. Corros*., 2022, **73**, 1730–1751. doi: 10.1002/maco.202213140
28. N. Hossain, M.A. Chowdhury and M. Kchaou, An Overview of Green Corrosion Inhibitors for Sustainable and Environment Friendly Industrial Development, *J. Adhes. Sci. Technol*., 2021, **35**, 673–690. doi: 10.1080/01694243.2020.1816793
29. M.Y.M. Zaghloul, M.M.Y. Zaghloul and M.M.Y. Zaghloul, Developments in Polyester Composite Materials – An in-Depth Review on Natural Fibres and Nano Fillers, *Compos. Struct*., 2021, **278**, 114698. doi: 10.1016/j.compstruct.2021.114698
30. J. Li, P. Zhou, H. Shi and L. Wang, Influence of Filler Metal on Microstructure and Properties of Titanium/Copper Weld Joint by GTAW Weldments, *Mater. Sci. Eng. A*, 2022, **833**, 142508. doi: 10.1016/j.msea.2021.142508
31. Z. Yan, S. Chen, F. Jiang, O. Tian, N. Huang and S. Zhang, Weld Properties and Residual Stresses of VPPA Al Welds at Varying Welding Positions, *J. Mater. Res. Technol*., 2020, **9**, 2892–2902. doi: 10.1016/j.jmrt.2020.01.040
32. D. Unsworth, R.G. Driver and L. Li, Measurement and Prediction of Residual Stresses in Welded Girders, *J. Construct. Steel Res*., 2020, **169**, 106007. doi: 10.1016/j.jcsr.2020.106007

33. D.E.P. Klenam, G.S. Ogunwande, T. Omotosho, B. Ozah, N.B. Maledi, S.I. Hango, A.A. Fabuyide, L. Mohlala, J.W. Van Der Merwe and M.O. Bodunrin, Welding of Magnesium and Its Alloys: An Overview of Methods and Process Parameters and Their Effects on Mechanical Behaviour and Structural Integrity of the Welds, *Manuf. Rev.*, 2021, **8**, 29. doi: 10.1051/mfreview/2021028
34. N. Sreevidya, S. Abhijith, S.K. Albert, V. Vinod and I. Banerjee, Failure Analysis of Service Exposed Austenitic Stainless Steel Pipelines, *Eng. Faiure. Anal.*, 2020, **108**, 104337. doi: 10.1016/j.engfailanal.2019.104337
35. T.DebRoy, T. Mukherjee, H.L. Wei, J.W. Elmer and J.O. Milewski, Metallurgy, Mechanistic Models and Machine Learning in Metal Printing, *Nat. Rev. Mater.*, 2021, **6**, 48–68. doi: 10.1038/s41578-020-00236-1
36. S. Pourhashem, F. Saba, J. Duan, A. Rashidi, F. Guan, E.G. Nezhad and B. Hou, Polymer/Inorganic Nanocomposite Coatings with Superior Corrosion Protection Performance: A Review, *J. Ind. Eng. Chem.*, 2020, **88**, 29–57. doi: 10.1016/j.jiec.2020.04.029
37. N.M.R.N.M. Daud, K.K. Eng, K. Jumbri, A.M. Nor, M.F. Suhor, N.Borhan, A.Z. Abas, M.F. Aizamddin, M.J. Mohd Pu’ad and M.F. Muhammad, Benchmarking the Impact of Nickel Filler Addition, Weld Hardness, Environmental PH, and Corrosion Inhibitors on A333 Carbon Steel Pipe Weld Corrosion, *Results Eng.*, 2023, **20**, 101633. doi: 10.1016/j.rineng.2023.101633
38. A. Sasikumar, S. Gopi and D.G. Mohan, Prediction of Filler Added Friction Stir Welding Parameters for Improving Corrosion Resistance of Dissimilar Aluminium Alloys 5052 and 6082 Joints, *Adv. Mater. Sci.*, 2022, **22**, 79–95. doi: 10.2478/adms-2022-0014
39. J.P. Oliveira, T.G. Santos and R.M. Miranda, Revisiting Fundamental Welding Concepts to Improve Additive Manufacturing: From Theory to Practice, *Prog. Mater. Sci.*, 2020, **107**, 100590. doi: 10.1016/j.pmatsci.2019.100590
40. A. Sharma, K. Sharma, A. Islam and D. Roy, Effect of Welding Parameters on Automated Robotic Arc Welding Process, *Mater. Today Proc.*, 2019, **26**, 2363–2367. doi: 10.1016/j.matpr.2020.02.507
41. Y. Huang, J. Huang, J. Zhang, X. Yu, Q. Li, Z. Wang and D. Fan, Microstructure and Corrosion Characterization of Weld Metal in Stainless Steel and Low Carbon Steel Joint under Different Heat Input, *Mater. Today Commun.*, 2021, **29**, 102948. doi: 10.1016/j.mtcomm.2021.102948
42. V. Haribalaji, G. Venkatesan, M. Asif.M, M. Pandian, R.Subbiah and S.Boopathi, Investigation on Corrosion and Tensile Characteristics: Friction Stir Welding of AA7075 and AA2014, *Mater. Today Proc.*, 2022, **66**, 743–748. doi: 10.1016/j.matpr.2022.04.037
43. Q. Ben, Y. Zhang, L. Sun, L. Wang, Y. Wang and X. Zhan, Wear and Corrosion Resistance of FeCoCrxNiAl High-Entropy Alloy Coatings Fabricated by Laser Cladding on Q345 Welded Joint, *Metals*, 2022, **12**, 1428. doi: 10.3390/met12091428

44. T.K. Kandavel, T. Panneerselvam, V. Govind and M. Ravikumar, A Study on Corrosion Behaviour of Various Modes of ATIG Welded Plain Carbon Steel, *Mater. Today Proc.*, 2022, **66**, 1303–1312. doi: 10.1016/j.matpr.2022.05.133
45. D. Bai, F. Liu, H. Zhang and J. Liu, Corrosion Behavior and Passivation Protection Mechanism on Different Zone of High-Nitrogen Steel Weld, *Mater. Lett.*, 2021, **300**, 130194. doi: 10.1016/j.matlet.2021.130194
46. H. Tristijanto, M. N.Ilman and P.T. Iswanto, Corrosion Inhibition of Welded of X – 52 Steel Pipelines by Sodium Molybdate in 3.5% NaCl Solution, *Egypt. J. Pet.*, 2020, **29**, 155–162. doi: 10.1016/j.ejpe.2020.02.001
47. P.L. Guo and L.G. Ling, Effect of Post-Weld Heat Treatment (PWHT) on the Intergranular Corrosion of ENiCrFe-7 Weld Overlay Cladding Materials, *J. Mater. Res. Technol.*, 2020, **9**, 8636–8645. doi: 10.1016/j.jmrt.2020.05.101
48. R. Yu, Y. Cao, H. Chen, Q. Ye and Y.M. Zhang, Deep Learning Based Real-Time and in-Situ Monitoring of Weld Penetration: Where We Are and What Are Needed Revolutionary Solutions?, *J. Manuf. Process.*, 2023, **93**, 15–46. doi: 10.1016/j.jmapro.2023.03.011
49. X. Zhang, X. Dou, Z. He, H. Jin, C. He and D. Zhang, Fabrication of Superhydrophobic Cauliflower-like Cu[Sbnd]Co Coating with Anti-Corrosion and Anti-Fouling Properties on B10 Copper–Nickel Alloy Welded Joint, *Surf. Coat. Technol.*, 2023, **474**, 130121. doi: 10.1016/j.surfcoat.2023.130121
50. R. Ranjan and A.K. Das, Protection from Corrosion and Wear by Different Weld Cladding Techniques: A Review, *Mater. Today Proc.*, 2022, **57**, 1687–1693. doi: 10.1016/j.matpr.2021.12.329
51. H.M.H. Farh, M.E.A.B. Seghier and T.Zayed, A Comprehensive Review of Corrosion Protection and Control Techniques for Metallic Pipelines, *Eng. Failure Anal.*, 2023, **143**, 106885. doi: 10.1016/j.engfailanal.2022.106885
52. S.J. Ko, S.R. Choi, M.S. Hong, W.C. Kim and J.G. Kim, Effect of Imidazole as Corrosion Inhibitor on Carbon Steel Weldment in District Heating Water, *Materials*, 2021, **14**, 4416. doi: 10.3390/ma14164416
53. M. Messaadi, I. Grossoni, P. Shackleton, I. Shevtsov, Y. Bezin and R. Dollevoet, Rail Degradation Due to Thermite Weld Discontinuities: Field Experience, *Eng. Failure Anal.*, 2021, **128**, 105585. doi: 10.1016/j.engfailanal.2021.105585
54. O. Haievskyi, V. Kvasnytskyi, V. Haievskyi and C. Zvorykin, Analysis of the Influence of the Systemic Welding Coordination on the Quality Level Of Joints, *Eastern-European J. Enterp. Technol.*, 2020, **5**, 98–109.
55. S.H. Alrefaee, K.Y. Rhee, C. Verma, M.A. Quraishi and E.E. Ebenso, Challenges and Advantages of Using Plant Extract as Inhibitors in Modern Corrosion Inhibition Systems: Recent Advancements, *J. Mol. Liq.*, 2021, **321**, 114666. doi: 10.1016/j.molliq.2020.114666

56. A.O. Alao, A.P. Popoola, M.O. Dada and O. Sanni, Utilization of Green Inhibitors as a Sustainable Corrosion Control Method for Steel in Petrochemical Industries: A Review, *Front. Energy Res*., 2023, **10**, 1063315. doi: 10.3389/fenrg.2022.1063315
57. B.A. Abd-El-nabey, D.E. Abd-El-khalek, S. El-Housseiny and M.E. Mohamed, Plant Extracts as Corrosion and Scale Inhibitors: A Review, *Int. J. Corros. Scale Inhib*., 2020, **9**, 1287–1328. doi: 10.17675/2305-6894-2020-9-4-7
58. H. Kumar, V. Yadav and A. Kumari, Adsorption, Corrosion Inhibition Mechanism, and Computational Studies of Azadirachta Indica Extract for Protecting Mild Steel: Sustainable and Green Approach, *J. Phys. Chem. Solids*, 2022, **165**, 110690. doi: 10.1016/j.jpcs.2022.110690
59. B.Benzidia, M.Barbouchi, H.Hammouch, H.Erramli and N. Hajjaji, The Exploitation of Aloe Saponaria (Syn. Aloe Maculata) as a Potential Green Corrosion Inhibitor for Bronze in a Neutral Chloride Environment, *Biointerface Res. Appl. Chem*., 2023, **13**, 439. doi: 10.33263/BRIAC135.439
60. N.N.M. Phuong, T.T. Le, J. Van Camp and K. Raes, Evaluation of Antimicrobial Activity of Rambutan (Nephelium Lappaceum L.) Peel Extracts, *Int. J. Food Microbiol*., 2020, **321**, 108539. doi: 10.1016/j.ijfoodmicro.2020.108539
61. F. Gapsari, P.H. Setyarini, F. Kurniawan, A. Ahnaf, M.S. Anwar and U.K. Zuryati, Corrosion Inhibition of Weldment by Nephelium Lappaceum Peel Extract in 3.5% NaCl Solution, *S. Afr. J. Chem. Eng*., 2022, **41**, 223–232. doi: 10.1016/j.sajce.2022.06.006
62. F. Gapsari, D.B. Darmadi, P.H. Setyarini, H. Izzuddin, K.A. Madurani, A. Tanji and H. Hermawan, Nephelium Lappaceum Extract as an Organic Inhibitor to Control the Corrosion of Carbon Steel Weldment in the Acidic Environment, *Sustainability*, 2021, **13**, 12135. doi: 10.3390/su132112135
63. K.K. Veedu, S.Mohan, S.B.Somappa and N.K. Gopalan, Eco-Friendly Anticorrosive Epoxy Coating from Ixora Leaf Extract: A Promising Solution for Steel Protection in Marine Environment, *J. Cleaner. Prod*., 2022, **340**, 130750. doi: 10.1016/j.jclepro.2022.130750
64. N. Bhardwaj, P. Sharma and V. Kumar, Phytochemicals as Steel Corrosion Inhibitor: An Insight into Mechanism, *Corros. Rev*., 2021, **39**, 27–41. doi: 10.1515/corrrev-2020-0046
65. N. AbdelRahman, M. Bekhit, N.A. Negm and Z.I. Abdeen, Synthesis and Evaluation of Polymeric Dispersant Based on Vegetable Oils Their Application as Cutting Fluid, *Egypt. J. Chem*., 2021, **64**, 5537–5545. doi: 10.21608/ejchem.2021.74156.3662
66. R.N. Sarma and R. Vinu, Current Status and Future Prospects of Biolubricants: Properties and Applications, *Lubricants*, 2022, **10**, 70. doi: 10.3390/lubricants10040070
67. J.A. Cecilia, D.B. Plata, R.M.A. Saboya, F.M.T. de Luna, C.L. Cavalcante and E. Rodríguez-Castellón, An Overview of the Biolubricant Production Process: Challenges and Future Perspectives, *Processes*, 2020, **8**, 257. doi: 10.3390/pr8030257

68. K.C. Wickramasinghe, H. Sasahara, E.A. Rahim and G.I.P. Perera, Recent Advances on High Performance Machining of Aerospace Materials and Composites Using Vegetable Oil-Based Metal Working Fluids, *J. Cleaner Prod.*, 2021, **310**, 127459. doi: 10.1016/j.jclepro.2021.127459
69. G. Karmakar, P. Ghosh, K. Kohli, B.K. Sharma and S.Z. Erhan, Chemicals from Vegetable Oils, Fatty Derivatives, and Plant Biomass, *ACS Symp. Ser.*, 2020, **1347**, 1–31. doi: 10.1021/bk-2020-1347.ch001
70. A.A. Olufayo, V. Songmene, O.A. Olufayo and A.J. Akindele, Toward Promoting African Indigenous Additive Formulations to Vegetable Oil Based Cutting Fluids For Sustainable Machining, in: *Proceedings of the 22nd international conference and 42nd annual general meetings of the Nigerian Institution of Agricultural Engineers*, 2023, 525–535.
71. S.A. Shuvalov, Y.V. Porfiryev, D.S. Kolybelsky, V.A. Zaychenko, P.S. Popov, P.A. Gushchin, A.S. Mishurov, D.A. Petrova and V.A. Vinokurov, Nanoscale Functional Additives Application in the Low Temperature Greases, *Polymers*, 2021, **13**, 3749. doi: 10.3390/polym13213749
72. C. Verma, M.A. Quraishi and K.Y. Rhee, Natural Ligands: Promising Ecofriendly Alternatives for Corrosion Protection and Plethora of Many Prospects, *Process Saf. Environ. Prot.*, 2022, **162**, 253–290. doi: 10.1016/j.psep.2022.04.014
73. S.R. Yasa, S. Krishnasamy, R.K. Singh and V. Penumarthy, Synthesis and Characterization of *iso*-Undecenoic and *iso*-Undecanoic Acids Based Polyol Esters, *Ind. Eng. Chem. Res.*, 2017, **56**, 7423–7433. doi: 10.1021/acs.iecr.7b01760
74. V.S. Nagtode, C. Cardoza, H.K.A. Yasin, S.N. Mali, S.M. Tambe, P. Roy, K. Singh, A. Goel, P.D. Amin, B.R. Thorat, J.N. Cruz and A.P. Pratap, Green Surfactants (Biosurfactants): A Petroleum-Free Substitute for Sustainability – Comparison, Applications, Market, and Future Prospects, *ACS Omega*, 2023, **8**, 11674–11699. doi: 10.1021/acsomega.3c00591
75. E. Stavila, F. Yuliati, A. Adharis, J.A. Laksmono and M. Iqbal, Recent Advances in Synthesis of Polymers Based on Palm Oil and Its Fatty Acids, *RSC Adv.*, 2023, **13**, 14747–14775. doi: 10.1039/d3ra01913f
76. E.E. Ebenso, C. Verma, L.O. Olasunkanmi, E.D. Akpan, D.K. Verma, H. Lgaz, L. Guo, S. Kaya and M.A. Quraishi, Molecular Modelling of Compounds Used for Corrosion Inhibition Studies: A Review, *Phys. Chem. Chem. Phys.*, 2021, **23**, 19987–20027. doi: 10.1039/d1cp00244a
77. M. Freschi, A. Paniz, E. Cerqueni, G. Colella and G. Dotelli, The Twelve Principles of Green Tribology: Studies, Research, and Case Studies – A Brief Anthology, *Lubricants*, 2022, **10**, 129. doi: 10.3390/lubricants10060129
78. E. Faujdar and R.K. Singh, Methyl Oleate Derived Multifunctional Additive for Polyol Based Lubricants, *Wear*, 2021, **466–467**, 203550. doi: 10.1016/j.wear.2020.203550

♦ ♦ ♦