



MECHANICAL AND MORPHOLOGICAL FEATURES OF MICROWAVE HYBRID HEATING-INDUCED WELDING OF SS304 STAINLESS STEEL WITH COKE AS A SUBSECTOR

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Abstract

Electromagnetic radiation-assisted welding is an evolving welding process that has not been fully explicated in literature, considering the numerous arrays of existing materials. Based on this understanding, the eco-friendliness, energy conservation, and other benefits of this new welding method, this study was engineered. The paper studies the microwave hybrid heating technique in welding the austenitic SS304 stainless steel plates by utilizing a coke susceptor, Ni interface powder, and a sodium silicate-bound silica sand refractory over different microwave exposure times. The structural morphologies, tensile strength, hardness, and fracture behavior of the resultant SS304 joints were studied. The findings show that an increase in the microwave exposure time (15-18 min) causes a slight disparity in the proportion of elemental diffusion at the weld interfacial region. The prolonged microwave irradiation (16 - 18 min) improved the interface microhardness (135.51 - 160.45 HV) and the tensile strength (10.95 - 16.41 MPa) of the welded SS304 joints. This occurrence is associated with the improvement in the thermal-induced interdiffusion effect as the microwave volumetric heating is prolonged. The welds failed via the brittle failure mode, irrespective of the level of microwave exposure time.

Keywords: Microwave welding, stainless steel, microstructure, mechanical properties, fracture

Introduction

Attaining advancement in welding and joining necessitates a continuous search for a sustainable and innovative welding alternative with better cost-effectiveness, environmental friendliness, energy conservation, and efficiency. This has brought about the development of the microwave hybrid heating (MHH) technique, an alternative to conventional welding methods with a selective/focused and uniform heating capability (Naik *et al.*, 201; Sun *et al.*, 2018; Zhang *et al.*, 2024a; Zhang *et al.*, 2024b). The MHH technique is capable of achieving 90% less energy consumption relative to the traditional welding processes (Thakur *et al.*, 2022) and has successfully overcome microwave reflection experienced by bulk materials/metals exposed to direct electromagnetic radiation. The MHH employs electromagnetic waves (with 0.3 - 300 GHz frequency and 1 - 1 mm wavelength) (Naik *et al.*, 201; Tiwary *et al.*, 2023; Nandwani *et al.*, 2020;

Patel *et al.*, 2024; Liu *et al.*, 2024; Singh *et al.*, 2024) and energy to join metallic materials enclosed in a shielding refractory material through an orifice filled with a microwave susceptor medium to facilitate dielectric/volumetric heating and welding. The susceptor medium absorbs and converts the microwave radiation into heat for metal joining via the volumetric heating phenomenon. This heating phenomenon ensures uniform heating and happens at the molecular/atomic level within a shorter time, which decreases the thermal gradient and its associated thermal stresses within weldments (Sahota *et al.*, 2011). This is different from the traditional heating associated with conventional fusion welding methods. Quite a few studies have explored the use of MHH in joining similar and dissimilar metals, but MHH has remained an emerging technique with good prospects and many unfilled research gaps.

Naik *et al.* (2021) reported that intermetallic compounds like Fe-carbides were formed at the weld zone of the MHH-welded MS/SS-316 steel joints, and complete melting of the interface powder led to the attainment of welds with good metallurgical bonding. This eventually produced a weld with a strength of 347 MPa and microhardness of 133 HV. Similarly, the welding of stainless and mild steels was also performed by Gupta *et al.* (2013) with the aid of tungsten carbide (interface material) and charcoal as the susceptor medium over a 600 s exposure time. A dense and uniform weld structure was reported to be obtained with the presence of precipitated phases such as NiSi, FeNi, and Fe₃C, which improved the properties of the joint. Up to 340 MPa and 11.7% values were obtained as the joint's tensile strength and elongation values. Kumar *et al.* (2020) investigated the MHH-welding of the SS304/SS316 plates with the 50 µm SS316 powder (filler medium) and charcoal powder (susceptor) for a 360s microwave processing duration. A homogeneous weld structure containing C, Fe, Cr, and Ni phases was achieved, and the hardness of the joint was about 380 HV, which was 72% more than that of the base alloy. In another investigation, Zhang *et al.* (2024d) described that the upsurge in the susceptor mass from 0.2 g to 0.4 g for the production of the SAC305 joints after 1 min exposure time yielded the shear strengths of about 43 and 42 MPa, respectively, whereas the strengths of 37 and 23 MPa were produced after a 4 min exposure time. This outcome was linked to the coarsened intermetallic compounds and grains in the welds when the exposure time and the susceptor mass were increased. Despite the 0.63% porosity in the MHH-welded Inconel 625 joints, a tensile strength of about 324 MPa corresponding to about 36% of the base metal was still attained (Ranjan *et al.*, 2023). The weld zone was reported to be homogeneous and well-fused with the presence of Cr and niobium carbides. Zhang *et al.* (2024c) also scrutinized the role of dissimilar susceptors (susceptor variants) on the performance and properties of the MHH-welded

resistive heating and a quicker time in attaining a fusion state compared to the Ni interface material. Reddy *et al.* (2023) revealed that the use of the EWAC 1004 interface powder produced dendritic and columnar structures, while the SS-316L interface powder yielded equiaxed grains in the structure of the MHH-welded SS-316L joints. Also, higher grain size (up to 53%) and porosity level (up to 34%) were found in the welds produced with the EWAC 1004 interface powder.

Based on existing studies, it is imperative to have a detailed understanding of microwave-substrate/material interactions and the control of microwave-induced heating to further advance knowledge frontiers in metal joining. In the recent review of Tayier *et al.* (2022), it was provided that the key parameter settings and heating design models for the MHH applications have not been sufficiently expounded. More research is still needed on process parameters associated with the MHH technique. As an emerging welding alternative, the roles of microwave and MHH processing parameters like microwave heating/exposure duration, power level, type of susceptor, and interface material are research areas that still require thorough clarification in the literature. As a result, this paper investigates the use of the MHH technique in welding SS304 stainless steel with a coke susceptor, Ni interface powder, and a sodium silicate-bound silica sand refractory at a varied microwave exposure time. The structure, mechanical properties, and fracture behaviors of the resultant MHH-welded SS304 joints were appraised in this paper.

Materials and Methods

A 2 mm thick SS304 stainless steel plate was employed for this study. The elemental compositions of the plate are provided in Table 1. Through hydraulic guillotine-assisted metal shearing, the stainless-steel plate was dimensioned to 100 mm by 30 mm plates and then cleaned with acetone-soaked cotton wool to remove dirt.

The masking of the SS304 plates was performed before the microwave hybrid heating (MHH) and

Table 1: Chemical composition of SS304 plate in wt%

Alloy	Fe	Cr	Mn	Ni	Si	Mo	C	P	S
SS304	71.1	17.70	0.84	7.95	0.21	0.17	0.05	0.04	0.001

Cu/Sn-Ag-Cu/Cu joints. It was found that the shear strengths of the joints produced with the charcoal and SiC susceptors were about 91% and 75% of that of the graphite-produced joints, respectively. Rawat *et al.* (2022) simulated microwave hybrid heating using different interface materials (Ni and Inconel 718). It was found that the Inconel exhibited better

welding of the plates. This was achieved with the design and development of masking refractory moulds with two halves using silica sand, sodium silicate (binder), and carbon dioxide (CO₂) gas as a curing agent. Figure 1 shows the masking refractory development stages. It commences from the fabrication of the wooden frame (see Figure1a) for

the development of the mould halves (drag and cope) in Figure 1b-d. A stepped cavity was created in the drag to accommodate the overlapped geometry of the cut SS304 plates (see Figure 1b). A through-hole was also created at the centre of the cope for the introduction of the susceptor into the mould arrangement. Figure 2 is a representative

(with a 75:25 ratio) was prepared in a slurry-paste form. This paste was then evenly spread on the overlapped area (30 mm × 30 mm) between the SS304 stainless steel plates as an intermediate medium. The prepared workpieces (with intermediate medium) were then placed in the drag cavity and then covered with the opposite half (the

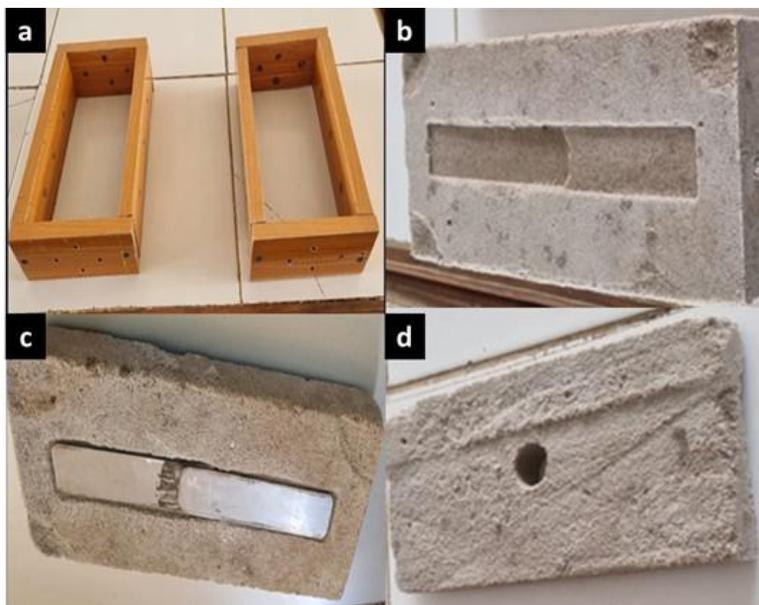


Figure 1: Masking refractory development (a) wooden mould frame, (b) mould's drag/bottom half with a cavity, (c) mould's drag/bottom half with lapped SS304 steel plates, (d) mould's cope/top half with susceptor-hole

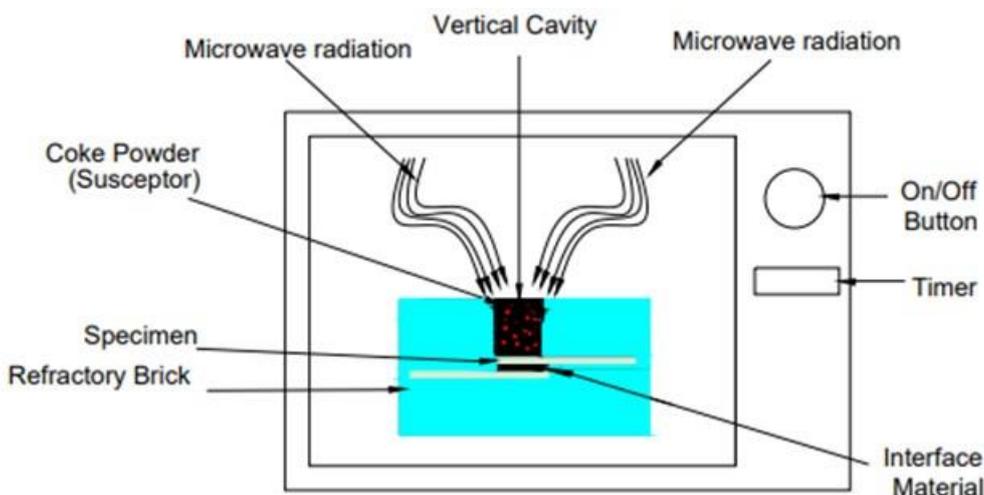


Figure 2: Pictorial illustration of the microwave hybrid heating of the SS304 stainless steel plates

illustration of the MHH system employed for this study.

The 20 µm particle-sized Ni powder (99.9% pure) was utilized as the interface/intermediate material for the microwave welding of the SS304 stainless steel plates. The Ni powder-epoxy resin mixture

cope) of the mould. The through-hole in the cope was filled with the coke powder (susceptor).

Meanwhile, the coke was obtained as irregular lumps from Ajaokuta Steel Company Limited (primarily used for blast-furnace ironmaking), and the coke lumps were then broken and ground to a

powder-like appearance in a metal mortar with the aid of a steel pestle. The ground coke powder was applied as the susceptor medium for the MHH-induced welding.

The prepared weld setup was placed in a 2.45 GHz domestic Hisense microwave applicator with a 25-litre capacity for the MHH-induced welding of the SS304 stainless steel plates as revealed in Figure 3. The power level of the microwave applicator was maintained at 1000 W while the exposure time was varied between 16 and 18 min after the preliminary welding. The resultant weld samples were metallographically prepared and etched after the MHH and welding. The metallographic samples were then scrutinized in a Scanning Electron Microscope (SEM) with energy-dispersive X-ray. The microhardness of the welds was determined via the use of a Vickers hardness tester (with a 100 g load for a 10 s duration). With an Instron 3369 Universal Tensile Machine, the tensile strength of

the welds was identified at a 5 mm/min crosshead speed. The fracture behavior of the welds was examined by placing the failed tensile samples in SEM.

Results and Discussion

Characterization of Nickel Powder and Susceptor

The SEM-EDS results of the Ni powder are provided in Figure 4. The Ni powder consists of fine and spherical morphologies as displayed in the SEM images in Figure 4, while the EDS examination reveals the existence of both Ni and O. The high affinity of Ni for O may be the reason for the presence of O in the Ni powder.

Figure 5 displays the morphologies and the EDS analysis result of the ground coke powder. The coke powder has a variety of shapes ranging from a few fine spherical forms to irregular and angular forms as shown in the SEM images in Figure 4.



Figure 3: Weld setup and microwave processing (a) and (b) weld setup in microwave applicator, and (c) MHH and welding in a Hisense microwave applicator

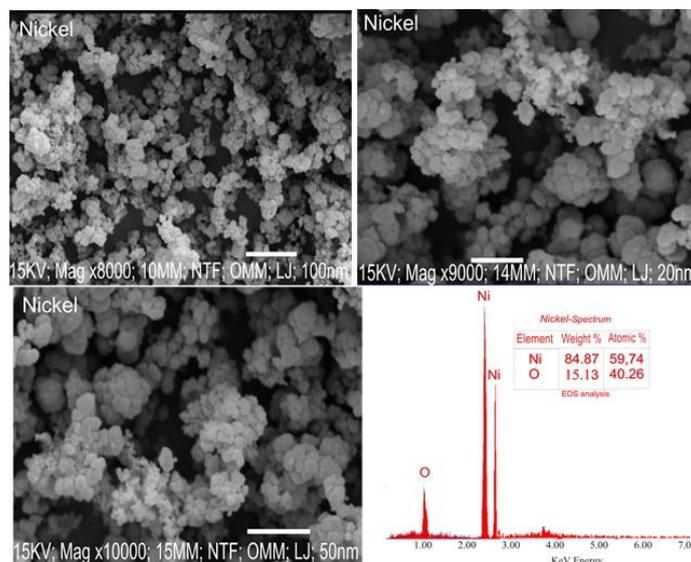


Figure 4: SEM-EDS results of the Ni powder

The coke has a predominantly high wt.% of C with other elements like O, K, and Fe in the EDS result (see Figure 2). The presence of K could be associated with the inherent ash in the coke lump, while the characteristic surface oxidation after coke production could have influenced the O content in it. The Fe traces in the coke powder may be linked to the wear of either the mortar or the pestle employed for grinding the as-received coke lumps.

Post-Weld Assessment

Figure 6 reveals the post-microwave processed mould (plan view) and the welded SS304 stainless steel plates. Figure 6a confirmed the occurrence of

coke-induced microwave hybrid heating directly above the overlapped area of the masked SS304 stainless steel plates due to the presence of the red-hot coke within the through-hole of the cope (see Figure 6a). It is adjudged that the molecular excitation within the coke powder after the microwave irradiation facilitated the heating of the coke up to a red-hot state, and this, in turn, raised the temperature of the SS304 substrate to establish the requisite microwave hybrid heating and the eventual welding of the substrate plates. It was observed that the level of the coke height in the cope's through-hole had gone down due to the combustion effect of the coke. After cooling of the mould, the mould's

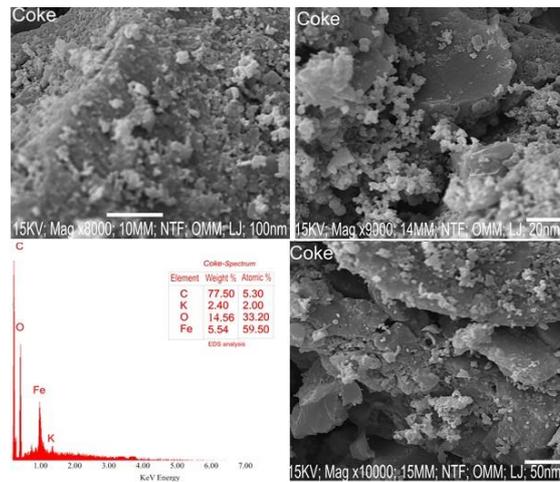


Figure 5: SEM-EDS results of the Coke powder employed as a susceptor



Figure 6: Microwave welded SS304 stainless steel plates

upper half (cope) was removed to reveal the appearance shown in Figure 6b. The overlapped regions of the weldments and their respective neighboring regions are darker in color (see Figure 6c) owing to the thermal radiation or the combustion/exothermic impact of the red-hot coke on the steel plates during the microwave processing stage. Also, oxidation of the steel surface could have played a role in the coloration of the steel plates since the welding process was not carried out in a vacuum environment. Meanwhile, there is no physical or palpable difference between the appearances of the MHH-welded SS304 stainless steel plates after changing the microwave exposure times between 16 - 18 mins.

Microstructure

The close-up views of the weld interfaces of the MHH-welded SS304 stainless steel plates obtained at different microwave exposure times are presented in Figure 7. The magnified appearances of the weld interface appear similar after increasing the exposure time to 18s but with more pore-like appearances in the sample subjected to 17s exposure time. The appearance of the interface could be associated with the evaporative effect of the moisture content/resin employed in positioning the Ni powder at the interface of the material before the welding. The presence of porosity level in the interface of the MHH-welded metallic joints has also been reported by a few researchers. A porosity level of up to 1.9% was reported to be found in the

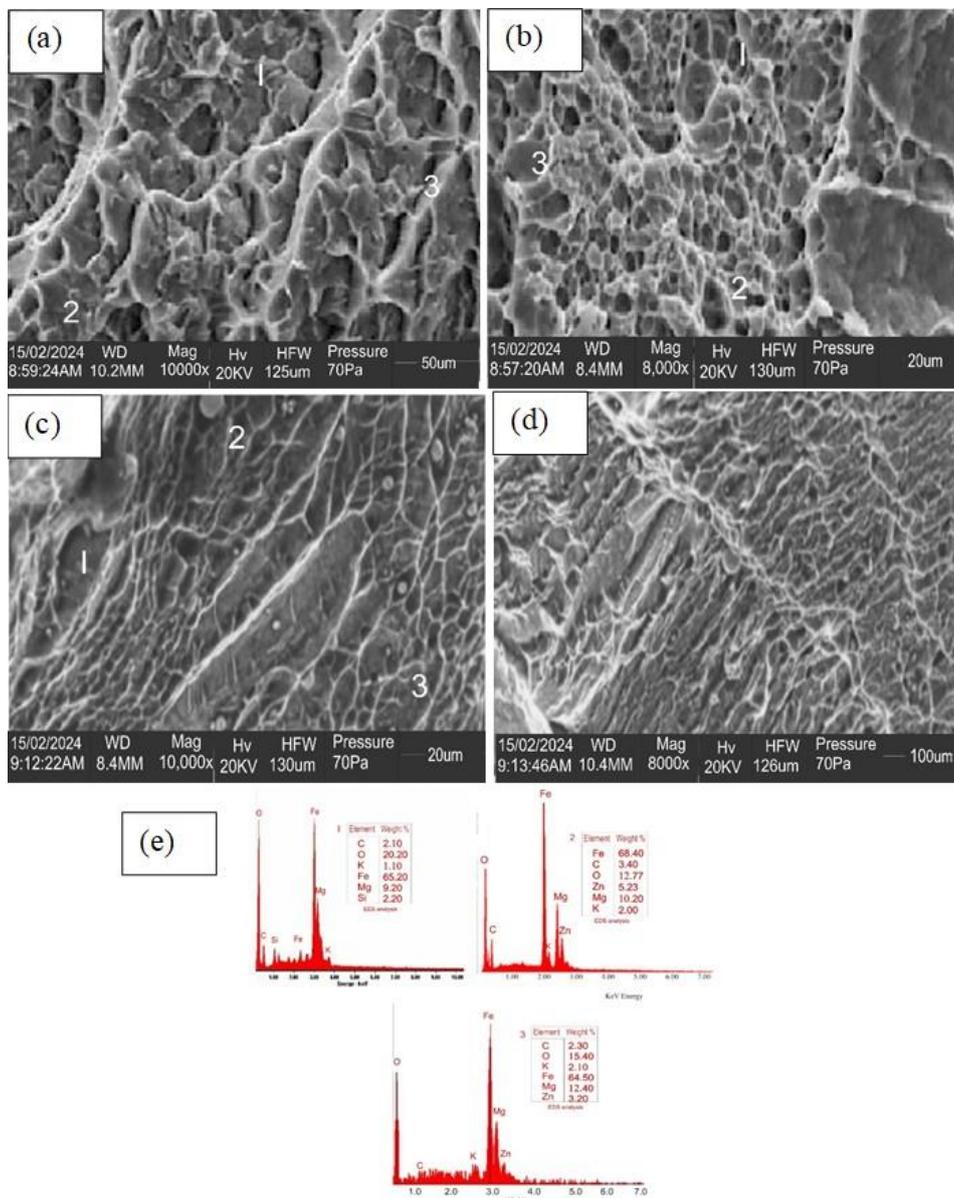


Figure 7: Interface structure of the MHH-welded joints (a-b) 17 min; and (c-d) 18 min, (e) point EDS results

microwave-welded Cu coin/Cu powder/Cu joints (Srinath *et al.*, 2011a) while in other studies, up to 0.78% and 0.94% porosity levels were found in the microwave-welded SS-316 stainless steel (Srinath *et al.*, 2011b) and SS-316/Inconel 718 joints (Bansal *et al.*, 2016a) respectively. Meanwhile, the effect of the microwave volumetric heating owing to the different exposure times caused a slight difference in the microstructure of the joint. Apart from the different appearances of the SEM images (see Figure 7), the EDS also confirmed a somewhat difference in the

while the respective average microhardness values are presented in Table 2. These results confirmed that the increment in the exposure time slightly improved the hardness of the weld interface and the neighborhood of the interface. This occurrence is obviously due to the enhanced (element) diffusion at the weld's interface and adjacent region as the microwave exposure time is increased. Precipitated phases and the grain structure of welds are typical factors that improve the weld zone's hardness. The improvement in the hardness of the microwave-



Figure 8: Schematic illustration of the hardness indentation location

Table 2: Microhardness values of the MHH-welded SS304 stainless steel joints

Hardness Location	Microwave exposure time	
	17 s	18 s
Interface	135.51 HV	160.45 HV
Close to the interface	163.18 HV	174.89 HV
Away from the interface	119.52 HV	114.78 HV

welds due to the slight differences in the wt.% of the elements found across the welds. Similar regions “1”, “2”, and “3” were marked on the SEM images in Figures. 7a-7c, while the point EDS analysis of these regions was carried out (see Figure 7e). The results confirm the presence of similar elements, while there was a slight disparity in the proportion of the elemental wt.%. This indicates that the closeness in the levels of the microwave exposure time and irradiation does not significantly alter the microstructure of the welded SS304 stainless steel joints. Apart from having a uniform and dense joint with diminutive pores or voids, phases such as NiSi, Fe₃C, and FeNi were identified in the weld zone of the mild steel/stainless steel joint, and these were linked to the improved properties of the joint (Gupta *et al.*, 2013). The elemental diffusion across the weld interface could also have aided the creation of the Fe-Ni phase at the weld zone of the joint.

Mechanical properties

The schematic illustration of the indented regions where the microhardness values were taken in the MHH-welded SS304 joint is presented in Figure 8,

welded Mild steel/SS316 joints was linked to the weld zone's dendritic structure and the precipitated carbides (Bansal *et al.*, 2016b).

Figure 9 reveals the shear strengths of the MHH-welded SS304 joints produced at dissimilar microwave heating times. The results confirm that the increment in the exposure time (15 - 18 min) of the microwave-irradiation improved the tensile strength (10.95 - 16.41 MPa) of the welded SS304 joints. This implies that the weld's ability to resist crack growth/propagation and failure is, to some extent, enhanced as the microwave exposure time is increased. This could be associated with thermal-induced interdiffusion between the interface and the base material during the microwave welding process. At a prolonged exposure time, the atomic excitation and diffusion will be enhanced, and this will facilitate better bonding between the substrate materials to be welded. However, the welds suffered a weaker load-bearing ability compared to the base alloy's tensile strength. This may be owing to the existence of porosity at the interface of the welds.

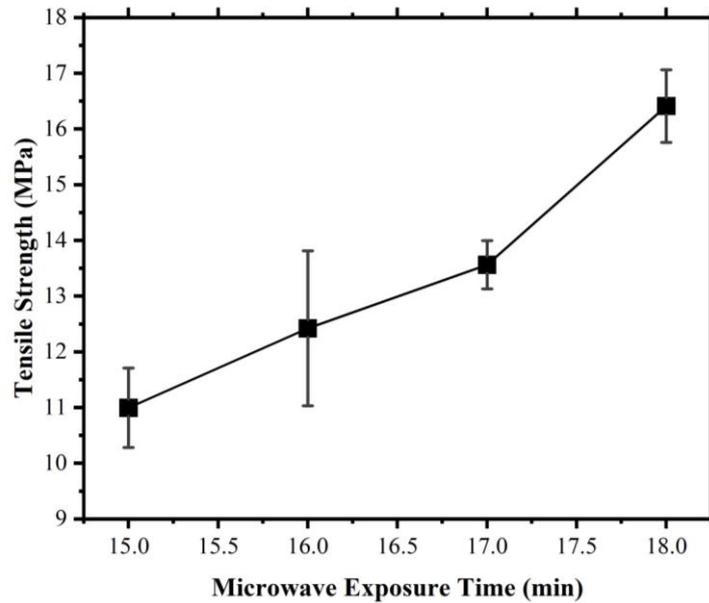


Figure 9: Tensile strength of the MHH-welded SS304 stainless steel joints at different microwave exposure times



Figure10: Fracture samples of the MHH-welded SS304 stainless steel joints at (a) 17 mins, and (b) 18 mins

The quality of microwave-welded joints can be influenced by many factors, such as the inherent precipitated phases, melting level of the interface medium, metallurgical bonding quality, and interfacial discontinuity/cracks (Bansal *et al.*, 2016a). The presence of interfacial discontinuity, like voids/pores, jeopardizes the load-bearing capacity of welds as these regions act as stress raisers that initiate and facilitate crack propagation and the eventual failure of the weld. In this study, the pores in the weld could be adjudged to have aided quicker failure of the welds under the tensile loading of the joints. To further understand this behavior, the weld's fractured surfaces after the tensile testing were examined in SEM.

Figure10a and 10b reveal the fracture appearances of the microwave-welded joints subjected to 17 and 18s exposure times after tensile loading. Sheet delamination fractures occurred at the weld regions of the SS304 specimens. This is a confirmation that the load-bearing capability of the weld is weak, and it also implies that crack initiation and quick propagation ensued at the bonded region of the welds during the tensile test. The inherent pores within the bonded interfacial zones of the welds could have acted as stress concentration sites, causing immediate crack initiation and coalescence during the tensile tests. This eventually results in quick-weld failures of the welds. Although the inherent phases in the weld are important, the

melting of the interface powder plays a leading role in establishing good bonding or weld quality. A good metallurgical bonding was acclaimed to be achieved in the MHH-welded stainless/mild steel joints on account of the complete melting or dissolution of the sandwiched interface Ni powder (Naik *et al.*, 2021).

The different coloration in the surfaces of the fractured samples (see Figure 10) may be indicative of the inhomogeneous melting of the interface Ni powder, which could have contributed to the low tensile strength of the welds. A close-up view of the fracture surfaces in SEM was carried out. Figure 11 reveals the SEM fracture images of the welds. It can

and the load-bearing performance of the MHH-welded SS304 stainless steel joints with the use of coke (as susceptor) is vital.

The low tensile strength of the joints indicates that the joints cannot be placed in a load-bearing service condition. Further studies are required to improve the load-bearing attribute of the joints, and this is part of the team's future research scope.

Conclusion

The microwave hybrid heating technique has been successfully utilized to join the austenitic SS304 stainless steel plates in this paper via the use of coke,

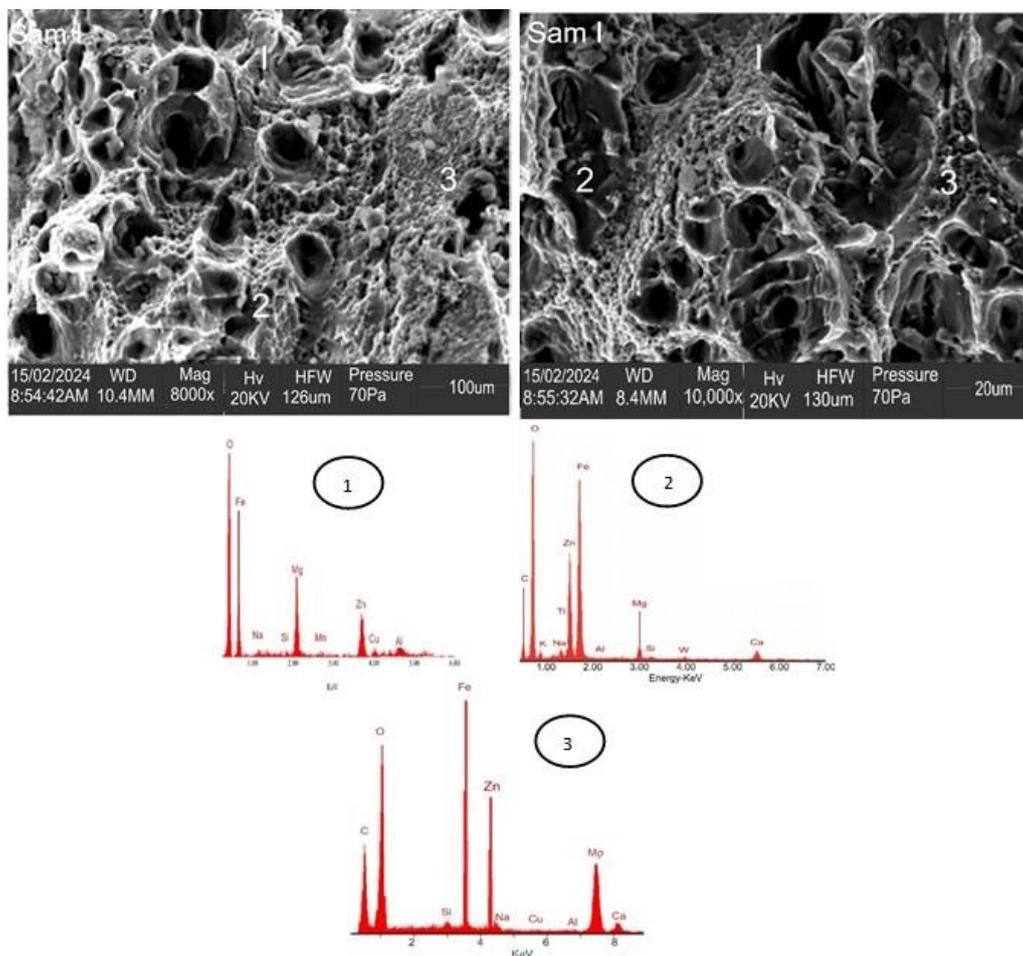


Figure11: SEM-EDS results of the fractured samples

be deduced from the observed SEM images that a brittle fracture, which is not homogenous occurred in the microwave welded joints irrespective of the microwave exposure time's level. The presence of such a fracture appearance has been identified as brittle failure in the studies of Tamang and Aravindan (2019). The point EDS results of the marked regions on the SEM images (see points "1", "2", and "3" in Figure 11) reveal the presence of Fe and O as the major elements. Improving the bonding

Ni powder, and SiO₂ as the susceptor, interface material, and masking refractory materials, respectively, at different microwave exposure times. The weld interface structure, tensile strength, hardness, and fracture of the welds were investigated. The conclusions of this investigation are briefly highlighted as follows:

- i. The microwave volumetric heating, owing to the different exposure times, caused a slight

difference in the microstructure of the joints due to the slight disparity in the proportion of the elemental wt.% present in the weld interface. Thermal-induced elemental diffusion is thus aided by the changes in the level of the microwave exposure time.

- ii. The increment in the exposure time (15 - 18 min) of the microwave irradiation improved the interface microhardness (135.51 - 160.45 HV) and the tensile strength (10.95 - 16.41 MPa) of the welded SS304 joints. This occurrence is linked to the improved thermal-induced interdiffusion between the base material during the microwave welding process.
- iii. All the welds fail via delamination and the fracture surfaces are characterized by brittle fracture appearances.

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