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Filler powder free joining of SAF 2507 using selective microwave hybrid heating technique

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Microwave Hybrid Heating (MHH) based joining of super duplex stainless steel (SAF 2507) with cross-sectional dimensions 3.5 mm ×3 mm has been carried out for the first time by using a microwave applicator of 900 W operated at 2.45 GHz for 400 s. Graphite rods have been used instead of traditionally used charcoal powder to serve as susceptor material. Graphite rods are good susceptor of microwave radiations therefore the presence of these rods helps in initiating and carrying forward the joining process. Moreover, the melting temperature can be achieved for specimens under investigations through this novel process thereby eliminating the need of using any filler powder. Absence of filler powder reduces the process cost significantly. The joints have been mechanically characterized by Vickers micro-hardness and physically characterized by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) tests. It has been observed through these tests that micro-hardness of the joints was more than the base alloy due to transfer of carbon from graphite rods to the joint zone.

Keywords: Micro-hardness, Microwave Hybrid Heating (MHH), SAF 2507, Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS)

1 Introduction

Super duplex stainless steel (SAF 2507) contains mainly Cr, Mo and Ni in different proportions. It has an outstanding corrosion resistance and mechanical properties therefore used in applications such as petrochemicals, seawater equipment and chemical processes etc., where special corrosion resistance and strength are required. Super duplex stainless steel is a mixed combination of austenite and ferrite phases based on the Fe-Cr-Ni structure and it shows a good weldability[1]. This super alloy exhibits outstanding properties and have been mostly used in to severe corrosive and high temperature working environments. Parts made of super alloys like SAF 2507 are very costly and it is not suitable to replace the whole part due to some minor defects. So, a novel joining process which makes it possible to process super alloys like SAF 2507 is a need of the hour. MHH is one such novel process which can be used to process a variety of alloys using microwave energy[2]. Qi *et al.*[3] have used the laser-metal inert gas hybrid welding method to join SAF 2507 specimens. After the joint formation the microstructure and mechanical properties were observed. Results showed that the arc/laser hybrid effect was more significant when the arc led the laser with 2 mm distance. Dissimilar joints of SAF 2507 plates and Inconel 625 have been investigated by Ramkumar *et al.*[4] through pulsed current and continuous current gas tungsten arc welding process. They compared the results of mechanical properties of weldment joined by ER2553 and ERNiCrMo-4 filler materials. SAF 2507 plates welding has been conducted by Qi *et al.*[5] using laser beam welding method. It has been determined that the enhanced pitting corrosion resistance is possible using laser beam welding in comparison to laser/gas metal arc hybrid joining weld. Friction stir welding has been used by Sato *et al.*[6] to examine the micro structural properties of SAF 2507 friction stir welded joints. Polycrystalline cubic boron nitride tool pin was used in that welding process. Mechanical results of joints showed increased value of strength and hardness found in the joint region, due to ferrite and austenite phases with small grain size.

Bagha *et al.*[7] have performed powder free joining of SS304 specimen plates by MHH to minimize cost of welding. Welded joints were physically and mechanically characterized. Improved hardness, strength and homogenous structure have been found in the weld zone. Dwivedi and Sharma[8] have optimized the welding through MHH of MS plates using nickel-based filler powder and examined tensile strength using different

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input process factors. Badiger *et al.*[9] have used Taguchi L16 OA to conduct experiments for joining Inconel-625 plates using microwave applicator run with 600 W and 900 W and found process factors effect on the mechanical properties like flexural and tensile strength of the joints. Size of filler powder played a major role in deciding the output properties. Badiger *et al.*[10] have also differentiated the joining process of Inconel-625 plates through microwave applicator run on 600 W and 900 W having 2.45 GHz frequency. Higher strength was found in the joints welded at low input power using 600 W in comparison to 900 W welded joints. Pal *et al.*[11] have calculated input factors effect on the mechanical properties of SS304/SS316 joints welded through MHH. Optimal micro-hardness and micro-tensile strength were achieved when the input parameters were set as SS304-SS304, 70 nm and 360 s for specimen material, filler powder size and process time respectively. Mondal *et al.*[12] have used grey relation based Taguchi method for joining of SAF 2507 by using TIG welding and examined tensile strength using different input process factors. Singh *et al.*[13] have used L9 OA to conduct experiments for joining of copper using friction stir welding and found process factors effect on the mechanical properties like impact and tensile strength of the joints. Kaliappan and Chidambarakuttalam[14] have differentiated the joining process of aluminum and titanium through gas tungsten arc welding using different environment conditions. Better mechanical properties have been found in the joints welded in argon environment in comparison to open environment condition. Kumar and Gandhinathan[15] have performed brazing of Ti-6Al-4V in vacuum furnace with the help of BAg-22 interface powder.

Higher shear strength was found at 780 ^{0}C in comparison to 720 ^{0}C and 750 ^{0}C temperatures brazed joints.

Many joining techniques have been used earlier for joining duplex type stainless steels such as laser beam welding[5], gas tungsten arc welding[4], flux core arc welding[16] and friction stir welding[6]. However, MHH based technique which is relatively new to the joining field has not yet been explored in full detail for joining SAF 2507. In this research work, we have performed microwave joining of SAF 2507 in the absence of any interface material. Investigation of weld has been conducted using mechanical characterization to examine quality of welded joints.

2 Materials and Methods

Joint's quality is very important in welding process so, proper selection of refractory bricks, joining time and susceptor material are vital to make good quality joint through MHH. Different types of arrangements of above factors were investigated for trial experiments. The following methodology was used for joining of SAF 2507 specimen plates by using MHH as shown in Fig. 1.

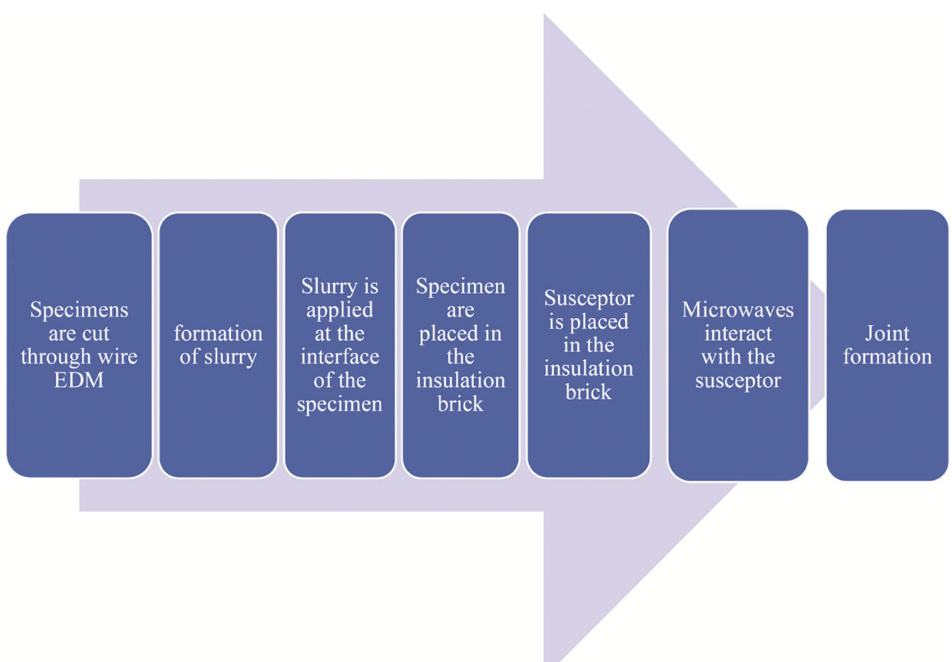

Fig. 1 — Flow chart of MHH based joining process.

Table 1 shows SAF 2507 composition details which was used as candidate material. Due to wide applications in oil and gas production, petrochemical, water desalinization, marine, chemical and power sectors, it is a very important alloy for industrial use. SAF 2507 plate was cut as per ASTM standard by using wire EDM into dimensions 50×3.5×3 mm^3 i.e., 50 mm total length, 3 mm thickness and 3.5 mm width as shown in Fig. 2. Graphite rods were selected in place of susceptor.

MHH was employed to perform experiments by using domestic multimode applicator of power 900 W functioned at 2.45 GHz frequency. Table 2 shows detail of the procedure parameters used in microwave welding method. It also shows the number of graphite rods used in the joining. The amount of the graphite rods selected was based on trial experiments. To house the candidate material into insulation brick, a cavity was cut. The refractory brick was used to mask the candidate materials. Bricks of thickness 4 cm were used. In this research work, candidate materials were successfully joined through MHH technique without any filler material. Mechanical characterization was done to check hardness of the joints.

Table 1 — Chemical composition of SAF 2507 weight %)

Element present	% composition
Ni	7.271
Cr	27.41
Mo	3.65
C	<0.001
P	0.024
S	<0.0002
Mn	0.694
Si	0.432

Table 2 — Microwave welding procedure parameters

Parameters	Description
Microwave oven	Multimode
Candidate material	SAF 2507
Microwave operated frequency	2.45 GHz
Microwave power	900 W
Microwave exposure time	400 s
Susceptor material	Graphite rods
Number of graphite rods	6

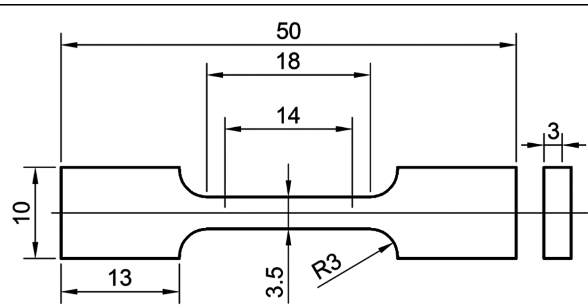

Fig. 2 — Specimen dimensions in mm.

Firstly, emery paper was used to grind candidate materials. Preheating of cleaned candidate material, refractory and insulation bricks were done in microwave oven for 2-3 minute to remove moisture content. Afterward, insulation brick cavity cut was filled with candidate material and shielded by using refractory brick. The entire assembly was placed inside microwave applicator.

The trials were conducted through microwave exposure 300-600 s with an interval of 50 s and observed that significant joint was formed at 400 s. Once the microwave oven was switched on susceptor material i.e., (graphite rods) started absorbing microwaves. After, absorption of microwaves, graphite rods got heated and transferred heat to joining region of the candidate material through conventional mode of heat transfer. At higher temperature, the skin depth of joining region got raised and initiated the absorption of microwaves. Because of higher temperature, joining region got melted and candidate material parts got diffused into each other. Once the microwave oven was switched off, cooling of the candidate material occurred and joints were welded after solidification.

3 Results and Discussion

SAF 2507 specimens were welded effectively by MHH-based welding method in the absence of any filler material. This unit comprised the physical and mechanical characterization outcomes performed on the microwave welded joints. SEM and EDS procedures were used to conduct physical characterization of welded joints. A very good quality joint formation took place that was as good as the base alloy. No separate heat affected zone could be distinguished from the SEM images. Figure 3 (a and b) shows the SEM image of the weld zone. In this SEM image, distinct weld zone or heat affected zone could not be located due to two reasons. One is that in this process of joining no filler powder was used and hence the microstructure of the joint was seen to be same throughout the weld zone. Secondly, the fusion at the interface took place very well and hence no clear cut boundaries between any zones could be visible. A reference dot (RD) was marked at the centre of the weld zone shown in Fig. 3 (a). RD was marked to locate the weld zone. EDS spectrum were also observed at three different locations marked as spectrum 1, spectrum 2 and

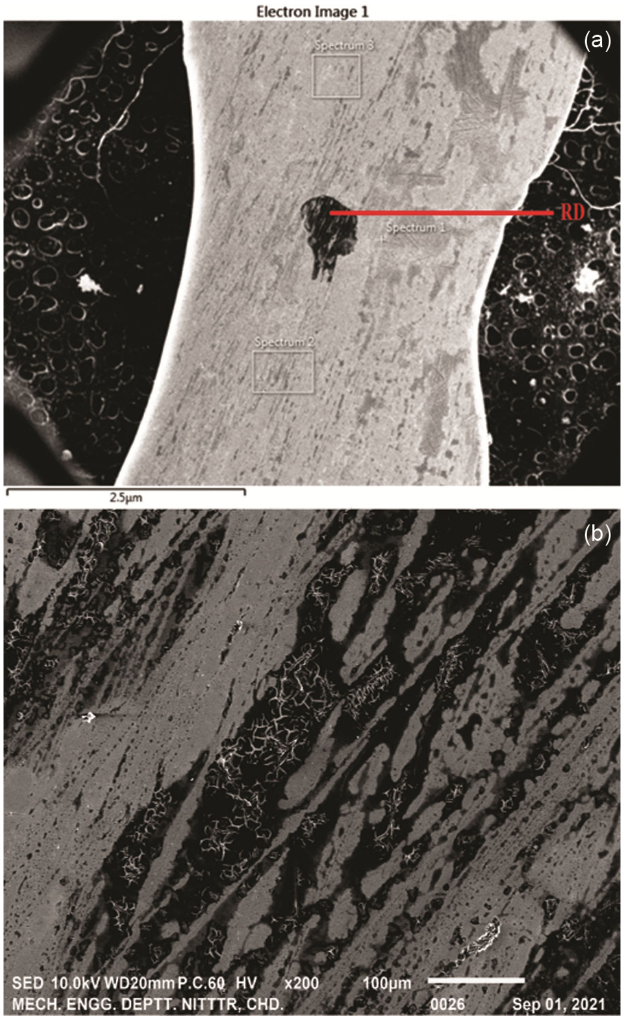

Fig. 3 — (a) SEM image of the weld zone showing different spectrum locations, and (b) SEM image of the 4th spectrum.

spectrum 3 as shown in the Fig. 3 (a). These spectrums along with the element composition tables are also provided in Fig. 4 (a-d) respectively. Spectrum 1 is at the weld zone, while spectrums 2 and 3 are little away from the weld zone as is clearly seen in Fig. 3 (a). As observed from the elemental composition of the three spectrums, there was no major difference in the composition at these three different locations. This is due to the fact that no filler powder was used at the interface of the specimens for joining. Another spectrum 4 was also observed as marked in Fig. 3 (b). This spectrum was taken at a location close to the edge of the specimen. Details of spectrum 4 can be seen in Fig. 4 (d), wherein, it can be seen that the carbon content was less than that in the weld zone but the rest of the composition was almost same. Increased carbon content at the weld zone was due to the addition of carbon from the graphite rods to the weld zone. MHH led to a strong metallurgical bond between two pieces of base material, due to volumetric heating nature of joining process. SEM results showed that appropriate fusion occurs at the specimen interface and fully fused weld formed. EDS tests result confirmed that the composition of the base metal and the weld zone was almost similar which further implies that no filler material was used in the joint formation.

The developed joints were polished and tested through mechanical characterization. Micro-hardness values were tested at different locations. The micro-hardness values increased in a direction towards joint area from the base metal area of welded joint. Load of 1000 g was used for 10 s to check micro-hardness of

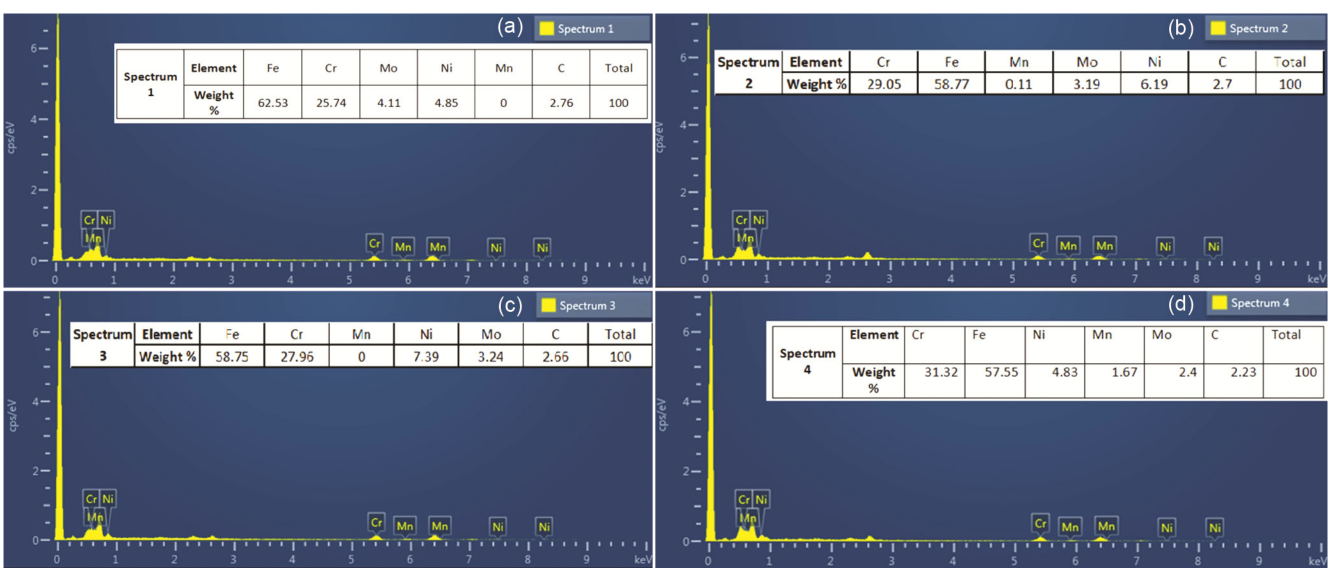

Fig. 4 — EDS spectrums of different locations.

Table 3 — Average micro-hardness value of welded specimen

Location	Average micro-hardness (Hv)
Base alloy	255
Weld region	415

weld through Vickers hardness tester. The average micro-hardness of welded specimen was tested shown in Table 3. From Table 3, it is found that joint area was much stronger and harder than base metal. The average micro-hardness at joint zone was tested 62.74% higher than base metal of welded joint. Value of hardness of weld zone was found higher in comparison to the base metal, because of absorption of carbon from the graphite rod.

4 Conclusion

Powder free welding of SAF 2507 has been successfully performed through MHH. Joining of SAF 2507 has not been performed by MHH before. Hardness of the weld zone has been found more than that of the base metal. The hardness of the weld zone has increased due to the increase in carbon content which has been observed from EDS results. SEM analysis has shown that a strong metallurgical bond has been formed between two pieces of base material. EDS test results have confirmed that the composition of the base metal and the weld zone is almost similar which further implies that no filler material has been used in the joint formation.

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