Challenges in joining of metallic pipes using microwave hybrid heating

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Abstract. Microwave hybrid heating (MHH) is a distinct and emerging alternative joining technique used to join metallic materials compared to available conventional joining processes such as FW, TIG, MIG, etc. MHH shows significant characteristics such as selective and volumetric heating, lower processing time, eco-friendly processing against conventional joining. This paper aims to investigate the joining of 316L stainless steel pipes by incorporating micrometric size (45µm) of 316L stainless steel powder in between the faying surfaces of the candidate material. Charcoal as a susceptor material was placed at the joint zone and exposed to microwave energy at 2.45 GHz inside the domestic microwave applicator at 900 W power levels. The challenges and principles involved in joining SS 316 L pipes using MHH have been discussed and initial experimental observations have been analyzed.

1. Introduction

Metallic pipes are widely used to transport fluid of gases at different pressure and temperature in industries such as marine, chemical, food, petroleum, etc. The alloy pipe is used for such applications due to excellent mechanical properties and higher resistance to corrosion at elevated temperatures due to the addition of molybdenum. In manufacturing processes, the fabrication of continuous structure of metallic pipe is not a feasible way hence; the discrete pipes need to be joined using conventional joining techniques such as LBW, TIG, SMAW, etc. Presently, the use of conventional joining technique is well developed in terms of technical aspects, however; the fusion welding of thin-walled SS pipe is not convenient with such high energy processes which damage the joint area largely and deteriorate the mechanical and microstructural properties with the heat input due to the lower conductivity of SS pipe. Secondly, the problem associated with the sound joint formation of thin-walled pipes joint properties will be governed by operator skill and working conditions [1–3]. More processing time and energy consumption can be wasted in frequent rework during the maintenance of pipe joints, hence; industries are searching for a viable and alternative joining process to overcome such problems and join thin-walled SS pipes with good reliability of the joint. Recently, microwave hybrid heating (MHH) techniques emerge as a novel route of joining techniques for metallic material with advantages such as lower heat input, uniform joint heating, eco-friendly joint formation, etc. as compared to conventional joining techniques. Use of microwave energy as an engineering tool in different field of application such as food processing, chemical synthesis, sintering, joining, etc. have been reported by many researchers with unique features such as uniform and selective heating characteristics, eco-friendly and energy-saving process, reduced processing time, better mechanical and metallurgical properties [4–18]. It has been appearing from the literature that microwave energy has the potential to address issues, related to metallic pipe joining. The microwave hybrid heating (MHH) technique
was reported first time in the form of Indian pattern in the year 2009 [13]. Later, in the year 2011, Srinath et al have reported the joining of copper plates by introducing copper powder as interface material [14]. The joint of the microwave welded copper plate shows higher joint strength than the strength of the TIG welded joint. The joint of SS-316 plates developed by MHH was reported, higher joint strength, and higher microhardness using the micrometric size of SS-316 powder [15] than Nickel powder [16]. The MS plates [17] and MS pipes [18] were joined using microwave energy by placing nickel powder (40 µm) as a sandwich layer and it was reported significantly joint strength. Similarly, dissimilar metal joining (SS 316 and MS) was also reported by the researcher with better joint strength and microhardness [6-7]. Inconel-625 alloy butt joint was developed using microwave energy by adding micron size nickel powder as interface material. The authors have reported that increase in specimen size also led to increase in microwave exposure time [9]. The available literature shows that the MHH technique is established as a metal joining process. The present paper reports the challenges encountered, basic principles of metallic joint development, and initial experimental results on SS 316L pipe joining using the MHH technique at 2.45 GHz and 900 W.

2. Challenges

Microwave processing of bulk metallic pipe is quite challenging, yet an interesting research area due to the unique heating characteristic of the microwave energy and its interaction with the materials. The literature on microwave joining of pipes is hardly available in this area. Microwave joining of metallic pipes required knowledge and fundamental aspects of microwave processing of materials. Control of MW energy in a particular application is a key issue for processing the material. The challenges encountered using microwave energy during the joining of metallic pipes are shown in Figure 1 and Table.1.

![Figure 1: Challenges encountered using microwave energy during the joining of metallic pipes](image)

2.1. Fabrication of fixture

In metal joining using MHH technique, the fixture designing plays most important role as it protect the metal from arcing and act as a masking material. Alumina based fire brick (ceramic material) is used for fixture as it is low dielectric loss substance which absorbs lesser amount of MW energy and shielded metallic pipes. It also supports the microwave energy to intensify at a joint area of the substrate material for selective heating as it holds the susceptor material. Designing of fixture consists of susceptor selection, masking material, the location and position of a fixture in the microwave applicator cavity and orientation of fixtures, etc. The microwave key characteristics such as uniform and selective heating solely depends on selection of fixtures materials whereas joint alignment, minimization of HAZ, application pressure etc. confined to positioning of fixture. The vertical position of the fixture as shown in Figure.2 provides better results due to ease of susceptor distribution around joint zone which promotes more uniform and selecting heating of the interfacing and joint area. In the horizontal positioning of the fixture, the susceptor placing
at the joint zone was difficult due to the circular geometry of the substrate. The thickness of the susceptor around the pipe was not maintained similarly hence; the non-uniform heating of the joint zone takes place leading to improper fusion of filler and base material.

2.2 Selection of susceptor materials
Susceptor materials such as charcoal powder, SiC, graphite, etc. plays very crucial role as it acts as a source of heat during MW irradiation. It must be a high dielectric loss substance that could be directly couple with microwave energy at room temperature when expose to microwave radiation and gets heated up very rapidly. Susceptor is placed at the joint area so that the fusion of materials ensure. The selection of susceptor material depends upon the characteristics such as higher heating rate, oxidation prevention, less contamination in the joint zone.

| Basis                | Challenges in metallic pipe joining                                                                 |
|----------------------|------------------------------------------------------------------------------------------------------|
| Physics              | Inadequate literature for better understanding of the microwave-metal interaction phenomena            |
| Interface materials  | Use of optimum size of the powder and quantity of filler materials which maintaining required porosity for better joint strength |
| Mathematical models  | Rarely available mathematical models to simulate behaviour of microwave processing effects in metal based materials |
| Handbook on Nano-size metal | Unavailability of microwave processing data hand book on nano-size metal                             |

3. Experimentation

3.1 Selection of materials
The use of SS pipe is worldwide due to its excellent mechanical and physical properties. The SS pipe encountered problems while joining with the conventional process due to changes in the microstructural
transformation due to higher heat input characteristics of the process. To control such a problem, the process required a higher vacuum which increases the cost of processing. The use of MW energy for joining material doesn't require vacuum as well as not affect the structural transformation of steel. Thus, the SS 316L pipe as shown in Figure 3 was selected as a candidate material for joining using MHH. The chemical composition of the SS 316L pipe is shown in Figure 3. Experimental trials were carried out in the domestic microwave applicators (Model: make: LG) with maximum power 900 W at 2.45 GHz to join commercially available SS 316L pipes having inner and outer diameter are 10 mm and 14 mm with pipes length 30 mm respectively.

![Figure 3](image)

**Figure 3:** As received (a) SS 316L pipe (b) SS 316L powder as interface material

The SS powder of micrometric size (45 µm) was used as an interface material in the butt joint. Table 3 show the chemical composition of as received SS 316L powder. An epoxy resin (Bisphenol - A based) was used as a binder with SS powder and forms slurry which was placed at faying surfaces of SS steel pipes. A susceptor (a high dielectric loss material) was used for hybrid heating of the pipe area to be joined. Charcoal was used as a susceptor material. Ceramic was used to develop a fixture for selective heating of the joint area and hiding the metallic pipes during the joining process.

### Table 3: Chemical composition of SS 316L pipes and powder

| Component | SS 316L Pipes | SS 316L Powder |
|-----------|---------------|---------------|
| C         | 0.015         | 0.05          |
| Mn        | 0.97          | 0.18          |
| Si        | 0.390         | 1.13          |
| Cr        | 16.56         | 17.90         |
| Ni        | 9.95          | 12.24         |
| Mo        | 1.97          | 2.90          |
| Fe        | Balance       | Balance       |

3.2 Development of joint

The slurry was prepared by adding approximately 10% of the binder (epoxy resin) in SS powder and was uniformly placed over entire surfaces of pipes to be joined. At the initial stage, slurry helps to bind the substrates and maintained the alignment of it. The binder used in the slurry also absorbed microwave energy and it gets evaporated above 300°C. There was no additional effect of epoxy resin observed in the formation of the pipe joint. Bulk metallic pipes reflect the microwave at room temperature due to lower skin depth; therefore, the masking material was used to cover the metallic pipes to avoid this problem. A susceptor that absorbs MW energy rapidly and acts as a source of heat when exposed to microwave irradiation. Due to the heating of the susceptor, the high heat was generated near the area to be joined. Bulk metals cannot directly coupled with microwave energy at room temperature hence, initial heating of interfacing materials and faying surfaces of the substrate taking place due to the transfer of heat from susceptor through conduction. Beyond critical temperature, metal directly absorb microwave energy and heating of metal taking place. Figure 4. Illustrate the schematic diagram of the experimental setup of the joining of SS pipes by MHH.
Figure 4: Schematic diagram of microwave joining of SS 316L pipes

After initial heating, metallic pipes reach critical temperature and start absorbing microwave energy resulting in the melting of the sandwich layer, and faying surfaces of pipes led to fusion and excellent bonding of candidate materials. The experimentation was carried out in a microwave applicator at the environmental condition. The details of microwave processing parameters are summarized in Table 2.

| Parameters          | Description          |
|---------------------|----------------------|
| Microwave frequency | 2.45 GHz             |
| Candidate material  | SS 316L pipes        |
| Interface material  | SS 316L powder       |
| Susceptor material  | Charcoal powder      |
| Exposure time       | 840-900 s            |
| Exposure power      | 900 W                |

4. Initial experimental results and discussion

The experiments were carried out using charcoal powder as a susceptor material and the initial observations of joining of SS 316L pipes using MHH are shown in Table 3. The microwave hybrid heating technique using different grade charcoal powder with different exposure times at 900 W powers. Activated charcoal powder (fine powder) with exposure time increases up to 900 s causes melting and sintering of interfacing powder with the faying surfaces of the SS pipes. The problem associated with the fine charcoal powder was the dispositioning of the powder after microwave processing. Due to light in weight, fine powder was not stick around the joint zone leading to improper heating of the joint as shown in Figure 5(c). The melting of sandwich powder was observed up to 900 s exposure times; however, no melting of the base metals was achieved. This can be attributed to the formation of an oxide layer at the joint zone which requires more heating to melt the faying surfaces of pipes. The hard coke powder gives the best result due to the proper covering of the joint zone even after microwave processing. It allows a good heating rate resulting in the melting of the interface powder and no oxidation was observed.
Table 3: Effect of susceptor materials and exposure time on joining of SS pipes at 900W power

| Sr. No | Susceptor     | Exposure time (s) | Results                                                  |
|--------|---------------|-------------------|----------------------------------------------------------|
| 1      | fine Charcoal powder | 540              | No joining                                               |
| 2      | fine Charcoal powder | 600              | No joining                                               |
| 3      | fine Charcoal powder | 780              | No joining                                               |
| 4      | fine Charcoal powder | 900              | Charcoal powder not sticks at the joint zone. Sintering of interface material with faying surface |
| 1      | Hard cock Charcoal powder | 600              | No joining                                               |
| 2      | Hard cock Charcoal powder | 840-900          | Melting of interface powder was observed. Joining of SS pipes was observed |

The exposure time below 840 s was insufficient to complete heating and melting of interfacing powder and the base metals with high density fire brick. However, appropriate fusion of base metal and interface powder was observed at 840 to 900 s as shown in Figure 6 (c). The rapid response, eco-friendly nature, and less time-consuming characteristics of microwave energy have attracted researchers to develop microwave processed products for industrial usages. The better understanding of process physics, mathematical models of the process, and control over environmental conditions in microwave applicators will help in achieving better quality, higher efficiency, and robust process design.

Figure 5: Location of (a) & (b) hard coke charcoal powder (c) fine charcoal powder.
5. Limitation

There are some limitations on which researchers have to deal with during the processing of metallic materials using microwave energy. The designing of a foolproof ceramic fixture is very essential as improper designing of fixture responsible for thermal damaging of the substrate; large size products cannot be processed due to fixed-size domestic microwave oven available. Processing of large size products required large microwave applicators which required higher investment. Microwave processing of metal is a newly developed technique due to which very little experimental data available, therefore it limits the flexibility of modeling and simulation of microwave processing and also leads to poor repeatability of experimental results that restrict the use of this process in Industrial applications. Microwave leakage is very harmful to humans hence precaution and safety measures should be followed during microwave processing.

6. Conclusions

The microwave hybrid heating (MHH) technique was used to join SS 316L pipes by incorporating 45 μm size of SS powder at 900 W power in a microwave applicator. The initial observations show that the joining of the pipe was obtained at 840-900 s exposure time with hard coke charcoal powder. The microwave joining process has been investigated by various researchers; however, the process is yet to be industrialized. The rigorous study of process physics and mathematical modeling tuned the process and used as an alternative source of the conventional pipe joining processes.

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