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Comparative experimental investigations on novel joining technology based on microwave energy to produce SS2205-SS2205 joints

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In this work, a novel joining technology has been developed by significantly modifying the existing older joining technology. Both methods have been based on using microwave energy. Metallic joints of SS2205-SS2205 have been developed by using the novel as well as old technology. In previous technology, formation of joints has been largely affected by the use of charcoal powder (susceptor), graphite sheet (separator) and filler powder (interface) for producing the joints. On the other hand, in the newly proposed method, the joints have been fabricated without using any charcoal powder, graphite sheet or filler powder. Graphite rods have been used instead of charcoal powder thereby improving speed and cleanliness of the process. Further, absence of charcoal powder has helped in getting rid of the charcoal feeder as well as the separator sheet; thereby ensuring an easier assembly set-up and reduced set-up time. Finally, filler powder has not been used in proposed method, thereby drastically reducing the material cost. Joints' microstructure and mechanical properties have been characterized. Newly proposed method-based joints have been observed to possess better hardness, tensile strength and ductility due to better microstructural composition despite lower carbon content. Hardness, tensile strength and percentage elongation have also been observed to be better than previous results by 8%, 16.67% and 17.85%, respectively.

Keywords: Characterization; Graphite rods, Metallic joints, Microwave hybrid heating, Susceptor material

1 Introduction

Duplex stainless steel (SS2205) has been used in harsh, acidic and corrosive environments, where austenitic stainless steel cannot sustain long life.[1] SS2205 has double the yield strength, excellent ductility, and toughness as compared to the austenitic stainless steel (SS304).[2]Due to the lower nickel content in SS2205, the manufacturing cost of SS2205 has also been found to be lower than that of SS304. The joining of metallic components has been observed to be vital in the fabrication of bigger products or structures in various manufacturing industries, especially to reduce the overall manufacturing cost.

SS2205 components have been joined together through various techniques in many industrial applications, such as different parts of an automobile, nuclear power plant, marine engineering, medical equipments, and chemical industry sector.[3]Major challenges in joining of SS2205 have been arising due to the number of embrittling precipitates and metallurgical changes during the heating process. Earlier, SS2205 specimens have been joined through different joining processes such as submerged arc welding[4], tungsten inert gas welding[5], plasma arc welding, electron beam welding[6], laser beam welding[7]and friction stir welding.[8,9] These joining techniques have some drawbacks, such as high set-up cost, inappropriate welding conditions, imbalance phase ratio of austenite/ferrite leading to cracks during solidification[10], corrosion susceptibility, and lower ductility.[11] The heating cycle in the welding process has been significantly affecting the properties of the welded joints. Obtaining the balance ratio between ferrite and austenite has been a critical issue in the weld ability of SS2205. Recently microwave energy has also been utilized in joining SS2205 based on an older joining technology (OJT) set-up.[12] Microwave-based joining has been seen to possess many benefits over other joining techniques, such as selective and volumetric heating, less joining time, reduced power consumption and desired microstructural properties.[13] In microwave-based joining, rapid and uniform volumetric heating has been achieved by transferring energy from the microwaves to the joining specimens.

Earlier, microwave hybrid heating (MHH) based joining has been utilized by many researchers in joining metallic specimens such as austenitic steel, aluminium, mild steel, copper and inconel etc. Use of

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metallic filler powders in MHH-based joining of metals and alloys have been reviewed by Kumar & Sehgal.[14] Gautam & Vipin[15] have studied the effects of input parameters on the joint properties of SS304-SS304 joints fabricated through the MHH-based joining process. Badiger *et al.*[16] have investigated the joining of Inconel 625 super alloy using nickel filler powder. Badiger *et al.*[17] have also optimized the process parameters using Taguchi grey analysis during the MHH-based joining process. Samyal *et al.*[18] have used the MHH-based joining process to fabricate the lap joint of SS202-SS202 during which the modal characteristics of the joints have also been explored. Thakur *et al.*[19] have joined the mild steel pipes through the MHH-based joining process wherein the mechanical properties of the joints have also been investigated.

Further, the effects of different filler powder sizes on the mechanical properties of SS304-SS304 joints fabricated by the OJT-based joining process have been reported by Bagha *et al.*[20] Smaller filler powder has been found to be helpful in achieving better mechanical properties for powder size varying from 50 μm to 20 μm. Bagha *et al.*[21] have also explored OJT-based filler-powder free joining of SS304-SS304. A solid metallurgical bond has been observed through scanning electron microscopy (SEM) results due to the interface region's overall melting. Pal *et al.*[22] have used nickel as interface powder of different sizes to join SS304-SS316 specimens by an optimized OJT-based joining process. As a result, homogenous and crack-free joints have been observed from SEM images. Kumar &Sehgal[23] have joined SS2205 specimens using the OJT-based joining process without any interface material. Handa *et al.*[24] have joined the Inconel 625 specimens through microwave energy using graphite rods as susceptor material. Singh *et al.*[25] have also attempted the filler powder-free joining of SAF 2507 through microwave energy.

While many techniques have been used in joining SS2205, including OJT, but the use of novel joining technology (NJT), having many advantages over OJT, has not yet been explored. The present investigations have fulfilled this research gap. Further, OJT has been used earlier in joining a variety of metals and alloys. Still, OJT has many limitations, including high material cost (filler powder), long set-up time (including drilling of charcoal feeder and its accurate placement vertically above the joint zone), longer processing time, untidy experimental set-up (due to the presence of charcoal powder). These limitations have been overcome in this work by the proposed NJT.[26] NJT has the benefits such as low cost, easy assembly, faster processing, and cleaner production. Compared to OJT, NJT-based joining has no requirement of filler powder resulting in reduced material cost. Since the graphite rods have been used over the conventionally used charcoal powder, the NJT-based joining process is cleaner. This work has achieved NJT-based joining of SS2205-SS2205 without using any costly filler powder. Further, no separator sheet has been used due to the absence of charcoal powder. The physical characterization of the fabricated joints has been done by SEM and energy dispersive spectroscopy (EDS) techniques. In addition, the mechanical property assessments have also been performed by micro-tensile and micro-hardness tests. The major motives of this work have been to reduce the material cost and process time in addition to developing a cleaner process. These three objectives have been very well attained in this work.

2 Materials and Methods

Proper selection of process parameters was an essential step in microwave joining to achieve the desired joint properties. For both OJT and NJT-based joining, SS2205 was selected as specimen material. These specimens were cut to an overall length of 50 mm, joint width of 3.5 mm, and joint thickness of 5 mm by wire electric discharge machining according to the ASTM standard E8 / E809. Processing time was kept to be varying between 600 to 750 seconds during the experiments at 30 seconds intervals. The joints were developed using a microwave applicator with 900 W power working at 2.45 GHz.

Figure 1(a) shows the schematic of the experimental set-up used during OJT-based joining. During OJT-based joining, refractory brick having length 100mm, width 50mm and thickness 30mm was used to accommodate the joining specimens as well as for insulation purposes; alumina brick having the same dimensions as that of the refractory brick was placed above the refractory brick containing the specimens to be joined; graphite sheet of 1 mm thickness was used as susceptor material. The refractory brick was placed at the central location within the microwave applicator cavity. A slot was made on top face of the insulation brick to accommodate the joining specimens, and nickel powder was used as a filler material to assist the joining process. Alumina brick had a centrally located

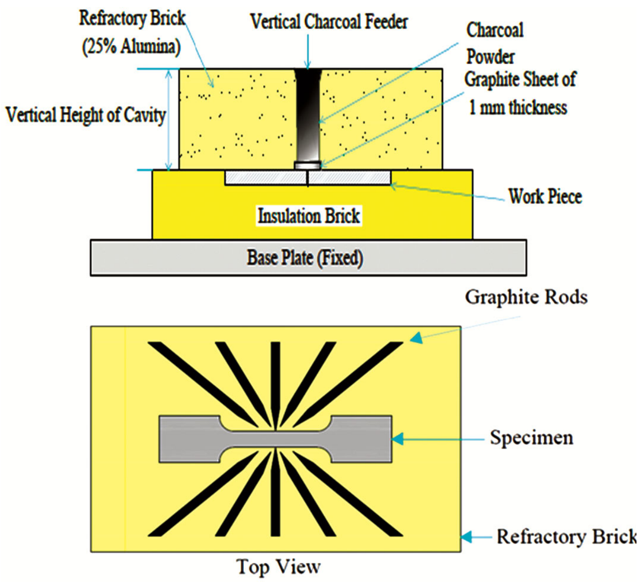

Fig. 1 — Schematic of experimental set-up used during (a) OJT-based joining, and (b) NJT-based joining.

vertical cavity type charcoal feeder (Diameter 8 mm) to supply the charcoal powder. The vertical-cavity type layout helped in heating the joining region selectively thereby rapidly heating the joining zone. Initially, the microwave radiations were absorbed by the charcoal powder as well as the nickel powder thereby creating an initial heating effect that was transmitted to the sample by conduction. After some time, the temperature of the ends of the specimens to be joined reached its critical value and hence the specimens began absorbing the microwaves directly. At this stage, the interface of the joint region was melted, and a strong joint was formed.

A new experimental set-up for NJT was used to fabricate the joints to increase the processing speed, ease of assembling process and reduce the material cost as shown in Fig. 1 (b). During NJT-based joining, the previous set-up was slightly modified by using ten graphite rods (diameter 2 mm; length 30 mm) instead of charcoal powder as susceptor material. The rods were placed horizontally around the joint zone as shown in Fig. 1(b). Heating effect produced by the graphite rods was so immense that it was self-sufficient to melt the joint zone without requiring any filler powder. Hence, the filler powder was not used at all thereby reducing the material cost. Alumina brick and its associated charcoal feeder was also not required thereby improving the cleanliness of this process. Refractory brick was used in place of alumina brick.Lastly, the NJT-based set-up did not require a graphite separator sheet.

During NJT-based joining, firstly, the specimens were cleaned using emery paper to remove specks of dirt or external particles. The insulation brick was placed inside the microwave applicator and pre-heated for two minutes to remove any moisture content from the brick. The insulation brick, containing the specimens along with the graphite rods, was covered with second refractory brick used as masking material. The graphite rods absorbed the microwave energy and transferred the heat to the joining region. The joining samples started absorbing the microwaves once their temperature reached the critical stage, followed by melting of the interface region, which caused the fusion of the specimens resulting in the formation of a solid joint.

3 Results and Discussion

Metallic joints of S2205-SS2205 were fabricated using two different types of experimental set-ups based on OJT and NJT and the joint characterization results were compared. In OJT-based joints, there was surface contact of graphite sheet with the joining specimen, so more carbon was transferred to the joints. Further, In NJT, graphite rods were in point contact with the joining specimens, so less carbon was induced into the joints. Additionally, charcoal powder used in OJT-based design had a more significant tendency to get transferred into the joint region rather than the ability of carbon elements to be transferred from solid graphite rods used in NJT-based design. NJT-based joints showed better micro-structural and mechanical properties than OJT-based joints due to the lower carbon content.

The joints were physically characterized by performing SEM and EDS tests. Micro-structural image of the joining region of OJT based joint was observed to be as drawn in Fig. 2(a). This image was taken at x500 zoom. The formation of grain boundaries of both ferrite and austenite phases was clearly visible in the image. Microwave hybrid heating produced volumetric heating, causing the melting of joining interfaces and resulting in a solid metallurgical joint between the specimens of the substrate material. SEM results affirmed the complete mix-up of interface and substrate materials in an OJT-based joint, as visible in Fig. 2 (a). The microstructure of the joint region was free from cracks, porosity and any other defects as observed from the microstructural analysis. SEM results revealed the accumulation of nickel powder used as filler powder in OJT-based joints in the austenitic phase. A continuous austenite network was defined as grain boundary austenite nucleating directly from the ferrite matrix. According to metallographic histology, ferrite is a body-centered cubic structure, austenite is a face-centered cubic structure, and austenite has higher carbon content than ferrite. In the joint region, balanced ferritic and austenitic phase balance was observed due to nickel being used as filler material in OJT-based joint.

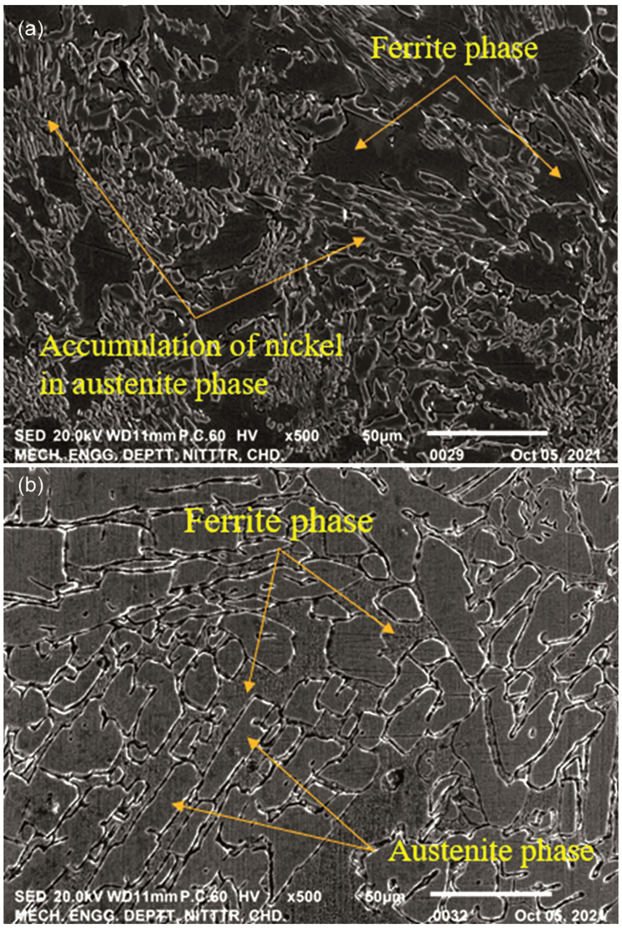

Fig. 2 — Scanning electron micrograph obtained after(a) OJT-based joint, and (b) NJT-based joint.

SEM image of the joint region of the NJT-based joint manufactured using graphite rods as susceptor medium was found to be as shown in Fig. 2 (b), which confirmed the complete fusion of base metal in the joint region. This image was also taken at x500 zoom. The formation of grain boundaries of both ferrite and austenite phases was clearly visible in the image. Since no interface powder was used with NJT-based joining, therefore an evenly distributed element of the joining specimen throughout the joint region was observed from the SEM image, which implied that the microstructure of the joint region was the same as the joining specimen. SS2205 alloy is a duplex (two-phase) stainless steel composed of both austenitic and ferritic phases. Duplex stainless steel solidified in a complete ferritic phase (first nucleation phase directly from a liquid) to form an austenitic phase below the ferritic solution temperature. Typical duplex SS comprised ferritic and austenitic phase fields. In most duplex SS compositions, the austenitic phase expanded, separating the ferritic phase into low and high-temperature ferrites. Generally, high-temperature ferrite is called delta ferrite, and low-temperature ferrite (produced by austenite transformation) is called alpha ferrite. The increase in austenitic content in the joint region was known to improve the ability to reduce the chances of failures due to fracture.

Various elements were present uniformly in the joint region of the OJT and NJT-based joints, which was confirmed as per results shown in Fig. 3 (a) and (b) respectively. The results confirmed the presence of significant constituents of base metal in the joining region from the colour codes of present elements. The

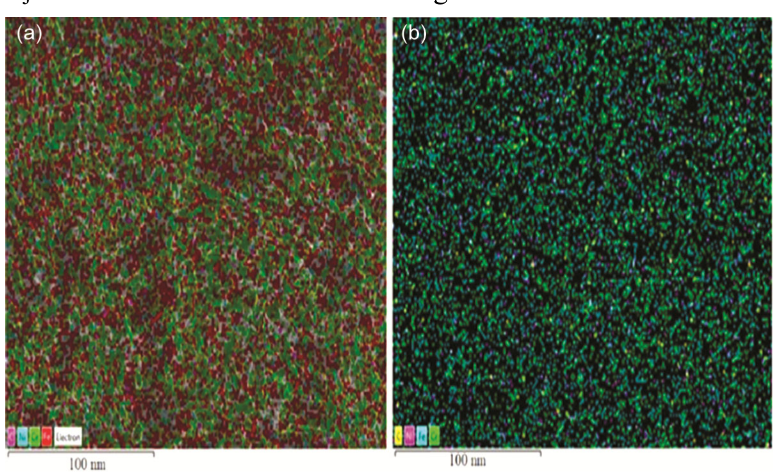

Fig. 3 — Presence of constituent elements in thejoint region during (a) OJT, and (b) NJT.

carbon content in the OJT-based joint was higher than that of the NJT-based joint because the carbon content of the austenite phase was higher than that of the ferrite phase. OJT-based joint mainly comprised austenitic phase whereas NJT-based joint comprised ferrite phase as revealed from EDS analysis. The EDS results also supported this observation as per Fig. 4.

The elemental composition of OJT-based joints was also investigated through EDS. Experimental results showed that the OJT-based joint possessed Cr, Fe, C Ni, Mn, Co, Cu, Si, Al and Mo with percent values as 23.87, 55.19, 9.14, 5.38, 1.05, 1.19, 1.05, 0.37, 0.17 and 2.59 respectively. The elemental analysis of the OJT-based joint described the complete diffusion of interface and base metal in the joining region. The EDS tests confirmed the presence of significant base metal elements in the joining region, which implied solid metallurgical bonding. The results of elemental composition analysis in the joining region relative to the base metal indicated that the as-received steel plate had lower nickel content. The variation of elemental composition revealed that the increase of nickel content in the joining region led to the enhanced phase transformation in the OJT-based joint.

The elemental composition of NJT-based joints was found to be containing Cr, Fe, C Ni, Mn, Co, Cu, Si, Al and Mo as 21.68, 62.25, 3.19, 4.70, 1.93, 1.07, 0.30, 0.49, 0.17 and 4.20 percent respectively. No significant difference between the elemental composition of the joint region and base metal was observed from the elemental analysis of the NJT-based joint. This was primarily due to the absence of any filler powder during joining process. The results of the EDS tests revealed that the base metal and joining region had nearly identical compositions, implying that no filler material was used in the joint formation. As the Cr / Ni ratio increased, the tendency to form ferrite increased and the type of solidification changed from austenite, austenite-ferrite to ferrite-austenite or ferrite. In the NJT-based joint, the microstructure was comprised mainly of the ferrite phase, as revealed from EDS analysis.

EDS results of an OJT-based joint manufactured using charcoal powder as susceptor medium were observed as shown in Fig. 4 (a). In the OJT-based joining, carbon got transferred from the charcoal powder and graphite sheet into the joining area, which had been confirmed by the presence of a significant amount of carbon content in the joint area, as revealed by EDS results. On the other hand, as per Fig. 4 (b), the EDS results of NJT-based joint manufactured using graphite rods as susceptor medium, confirmed

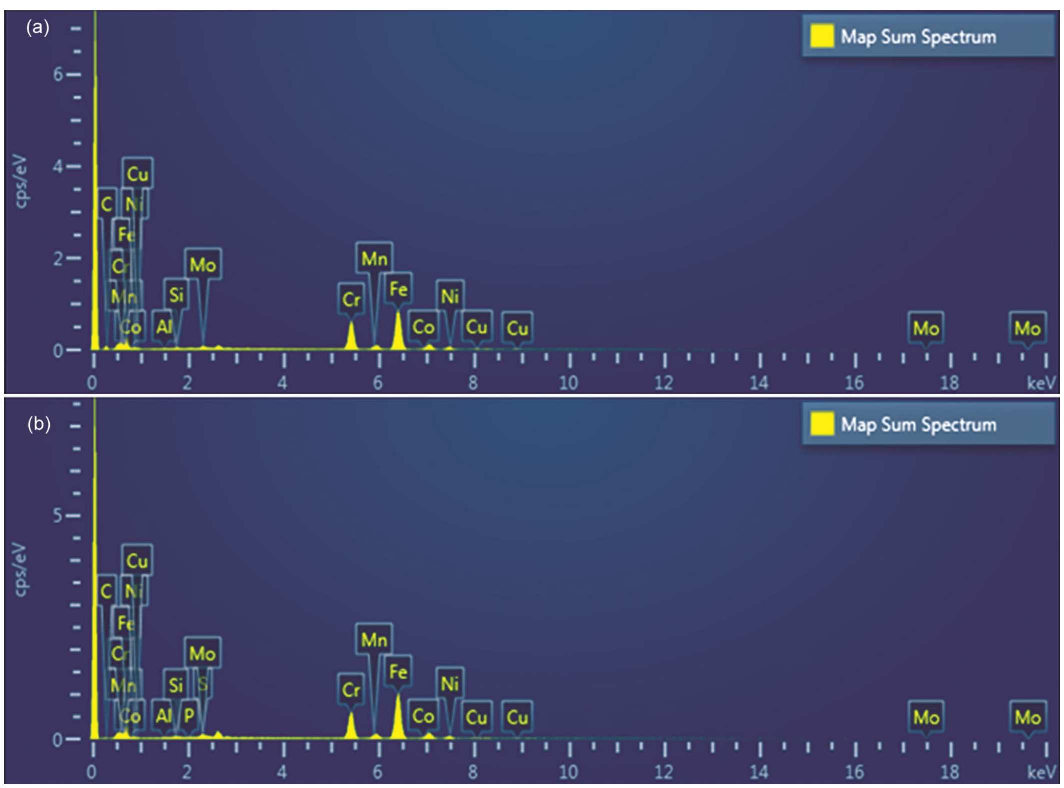

Fig. 4 — EDS spectrum of the joint region during (a) OJT, and (b) NJT.

low carbon content in the joint area due to lesser tendency of carbon transfer from the graphite rods.

The joints were tested for hardness using a Vickers micro-hardness test set-up with a diamond indenter for 1 kg load applied for 10 seconds. Three hardness measurements were taken at three different regions(joint region, heat affected zone and base region) of the joined specimens. Average hardness values of OJT and NJT-based joints were observed to be as shown in Fig. 5. The hardness of the joint region was found to be better than the hardness of the base specimen, as observed from the hardness results for both OJT and NJT-based processes. Overall, the hardness of NJT-based joints was more than OJT-based joints, mainly due to good metallurgical bonding. Elements like Mo, Mn, and Si were also responsible for the increase in hardness in NJT-based joints. NJT-based joints showed improved grain structure as observed from SEM results. This contributed to the improvement in the mechanical strength of the joint. NJT-based joints can be more suitable for wear-based applications where high hardness was needed.

Samples with a gauge length of 18 mm and a width of 3.5 mm were made according to standard procedures for performing the tensile tests. A micro tensile testing machine with a maximum force of 10 kN was used to determine the strength of the joints. The joints were exposed to 0.5 mm/min uniaxial extension rate. Figure 6 (a&b) present the average value of the joint tensile strength and elongation percentage respectively.

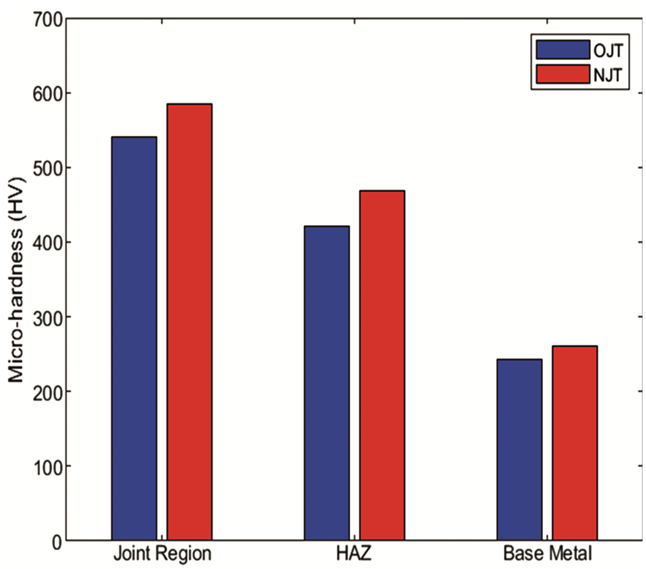

Fig. 5 — Hardness test results for joint region, HAZ and base metal zone.

The higher tensile strength of the NJT-based joint compared to the OJT-based joint was mainly due to good metallurgical bonding between the joining specimens. As observed from EDS analysis, an increase in the content of various elements composition like Mn and Mo was also responsible for higher strength in NJT-based joints. The NJT-based joint showed more ductility than the OJT-based joint, as revealed by mechanical characterization. For various applications where high strength was needed, NJT-based joints would be preferred. Also, NJT joints had lesser carbon content, which helped in attaining increased ductility as compared to OJT-based joints.

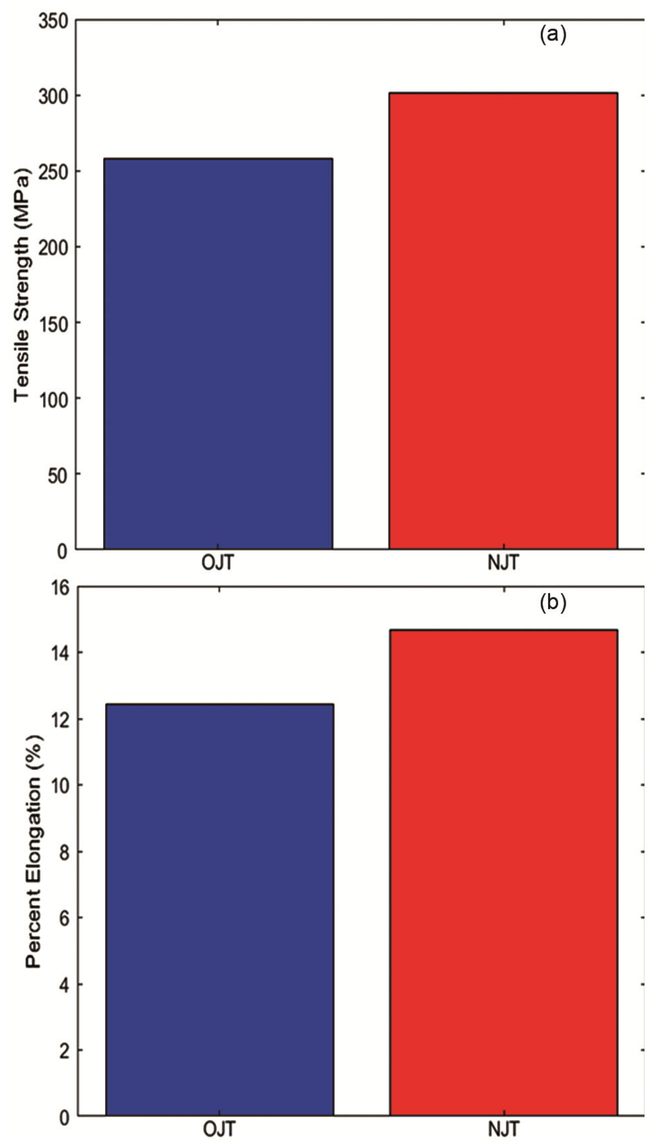

Fig. 6 — Mechanical characterization of joints (a) tensile strength, and (b) percent elonagtion

4 Conclusion

Similar joints of SS2205-SS2205 have been developed and compared as per two different joining technologies, namely OJT and NJT. The following conclusions have been drawn from this study:

- NJT-based joining has been revealed to be more economical and cleaner than OJT-based joining due to absence of the costly filler powder and charcoal powder respectively.
- Joining process has been observed to faster in NJT-based joining due to the quicker heating response produced by graphite rods as compared to the charcoal powder.
- Ease of assembling the entire set-up has been experienced to be better managed in NJT-based joining due to absence of vertical cavity type charcoal feeder and graphite sheet.
- The complete melting of the joining region to create a solid metallurgical bond has been depicted in microstructural images. Due to this, the joint region has been free of porosities, cracks, and defects. NJT-based joints have improved microstructural properties over OJT-based joints, as confirmed through the spectroscopy test results.
- Microhardness of the joint region has been found to be 584.66 HV in the case of NJT-based joining, whereas microhardness of the joint region has been found to be 541.33 HV in the case of OJT-based joining. NJT-based joints have been more suitable for wear-based applications where high hardness is required. Elements like Mo, Mn, and Si have been responsible for the increased hardness in NJT-based joints.
- The maximum tensile strength of 301 M Pa with 14.66 % elongation has been obtained in the case of NJT-based joining, whereas the ultimate tensile strength of 258 M Pa with 12.44 % elongation has been obtained in the case of OJT-based joining. NJT-based joints have better performance than their OJT-based counterparts for high-strength applications. Good metallurgical bonding between the joining specimens has resulted in high strength in the case of NJT-based joints. NJT joints also have lesser carbon content, which has been helpful in attaining increased ductility as compared to OJT-based joints.

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