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Application of graphite rods in producing Inconel 625 (UNS N06625) joints through the use of microwave radiation energy

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Microwave energy is very efficiently being harnessed to join metallic materials these days. Although, use of microwave energy to join metallic materials is in its initial stage but, it has led to an outstanding development in the field of manufacturing. In this research work, joining of Inconel 625 (UNS N06625) without any filler material has been performed with the help of a novel process by harnessing microwave energy from a 900 W microwave applicator. Major novelty of this work is the application of graphite rods in accelerating the joining process based on the use of microwave radiation energy due to which it could become possible to join the Inconel specimens without using any filler powder. Selective microwave hybrid heating has been performed using six graphite rods and the process time taken for successful joining of Inconel 625 specimens has been 360s. Three repetitions have been done using the mentioned process parameters. Mechanical characterization of the developed joints has been done with the help of Vickers micro-hardness tester and tensile testing machine. The mean microhardness of the joints has been observed to be 325.1 HV at the joint region which came out to be 10.32 % more than that of the base alloy. The mean ultimate tensile strength has been observed to be 319.9 MPa with mean elongation of 5.3% which has been observed to be less than that of the base alloy.

Keywords: Graphite rods, Inconel 625, Joining, Selective microwave hybrid heating

1 Introduction

Many engineering applications require materials to be employed under high temperature limits. These temperature limits can go even more than 1000°C and conventional materials are not able to tolerate such high temperature levels. Inconel 625 (UNS N06625) has a melting temperature range of 1280-1350°C and also has good oxidation resistance at higher temperatures. Inconel 625 is a super alloy constituting nickel as its main component and second main constituent is chromium. It has been predominantly known for high strength in tension and creep. All of the above-mentioned properties of Inconel 625 make it suitable for many applications such as turbine-blading, aircraft-ducting and engine-exhaust systems.

Materials which are exposed to extreme environments need to be joined more often when they undergo failure. Replacing the whole part after failure is sometimes not feasible due to high manufacturing cost of the component, high cost of the material itself and many other reasons. Inconel 625 is a nickel based super alloy. Due to its high cost, it is economically not possible to replace the whole part made up of such costly super alloy when some defect arises. So, a joining process with minimum limitations is a need of the hour. A few advanced methods of joining metals and alloys are gas tungsten arc welding[1–3], plasma arc welding[4], laser beam welding[5,6], electron beam welding[7], friction stir welding[8–10], flux cored arc welding[11]; although each of these techniques has its own pros and cons. Some parameters of the processes such as base metal thickness, type of filler material and welding skills play an important role in depicting the efficiency of the respective process. Also, the above-mentioned processes lead to substantial changes in the microstructure of the base material and joining region due to tremendous amount of heat energy input. This also leads to deterioration of some properties such as corrosion resistance and other mechanical properties. Even though, conventional techniques offer more flexibility and some other advantages also, but huge power consumption is also a matter of concern. So, a novel process is developed for productive joining of Inconel 625 without using filler material.

Microwave energy has been in use for some years for joining of metallic materials successfully. In Microwave Hybrid Heating (MHH), microwaves are harnessed to join the metallic materials. By harness it is meant that after leaving the magnetron portion, the microwaves get

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absorbed by the susceptor material. Absorption of microwaves by the susceptor material results into heating of that material and then the heat so produced is transferred to the metallic material through conventional heat transfer process. This transfer of heat to the metallic material increases its temperature to the limit when it itself starts absorbing the microwaves. This helps the material to melt and then joining takes place. MHH has a major advantage over other joining processes, which is volumetric heating. Direct conversion of microwaves into heat leads to volumetric heating which cannot be achieved in other joining processes wherein energy is transferred due to temperature gradients. Materials other than Inconel have also been successfully processed by some researchers. Some researchers have also explored the use of filler powder in manufacturing joints based on MHH.

Many researchers have carried out their research work on MHH. Bansal *et al.*[12] have successfully joined Inconel 718 specimens by MHH in a 900 W applicator and produced joints having 400 MPa tensile strength. Nickle Powder has been used as a filler material for joining. Characterization of the joint has been done using scanning electron microscopy (SEM), electron probe micro-analysis (EPMA) and X-ray diffraction (XRD). Joining surfaces were found to be well fused. This observation has been done with the help of back-scattered electron imaging micrograph.

Badiger *et al.*[13] have used microwave energy in joining Inconel 625. The authors also used nickel-based powder at joint interface during MHH based joining. Joint microstructure revealed that formation of carbides of chromium, molybdenum and nickel took place. Hardness of the interface region has been observed to be increased and accounted to the formation of the carbides of chromium. The hardness came out to be 350 HV. It has also been observed that 9.04% elongation took place while assessing the tensile strength, which came out to be 326 MPa. This tensile strength values were approximately 35% of the tensile strength values of base alloy. The fractured surface has also been examined and it has been noticed that plastic deformation took place and failure has been in a mixed mode.

Bansal *et al.*[14] have taken Inconel 718 specimens and joined them by using MHH. Inconel 718 powder has been used as interface joining material. After the joining has been accomplished, heat treatment has been carried out. This heat treatment has been done to improve the properties of the joint. It has been found that no cracks existed in the joint which has been associated to uniform heating. It has been observed that precipitation of strengthening phases in the matrix lead to the improvement of the mechanical properties. The ductility of the joint has also been enhanced after the specimen has been treated with the solution and aged treatment.

Badiger *et al.*[15] have concluded that complete bonding at the joint region took place with the help of MHH while joining Inconel 625 plates using Inconel 625 powder as a filler material. Presence of chromium carbide has been observed in between the base plates and fusion zone through XRD. Grain boundaries accommodated niobium carbide which has been detected with the help of energy dispersive X-Ray spectroscopy (EDS). About 245 HV average Vickers microhardness has been observed in the fusion zone. Also, about 0.7% porosity has been detected in the joint region. With elongation of 9.2% the measured value of the tensile strength has been 375 MPa. Ductility of the joint has been found to be sufficient because the specimen exhibited huge amount of plastic deformation before fracture while undergoing tensile test. Average impact toughness of 18 J has been observed at the joint with 377 MPa of maximum flexural strength.

Badiger *et al.*[16] have investigated the influence of input power on different parameters when specimens were joined by MHH. Inconel 625 has been chosen to be joined through MHH. Nickel based powder has been also used in this study as a filler material. On seeing the microstructure, it has been concluded that there were no cracks at the weld zone and complete fusion took place. 8% increase in tensile strength and 10% increase in flexural strength has been observed while using a 600 W applicator and compared to a 900 W applicator. It has also been found by fractography that the failure of the joints took place by mixed-mode fracture. More ductility has been observed in the joints which were prepared in a 600 W powered microwave oven.

After a diligent study of literature, it is concluded that so far Inconel 625 has only been joined with the help of filler powder which increases the cost of joining. Main aim of this work is to join Inconel 625 through MHH based method at a low cost without using any filler powder. Reason behind not using the filler powder is high-cost component associated with it. Also, MHH based joining until now has been carried out by using charcoal powder as the susceptor material. Due to the use of charcoal powder as susceptor, a separator sheet (usually made of graphite) is also required. Moreover, the use of charcoal powder makes it difficult to keep the process neat and clean. Therefore, graphite rods-based method has been used which does not require charcoal powder and graphite sheet. After the formation of the joints, mechanical characterization has been done using Vickers microhardness testing machine and ultimate testing machine.

2 Materials and Methods

Methodology adopted in this paper was summarized in Fig. 1. First of all, the specimens were cut to desired shape and size as per ASTM standard by using wire-cut electric discharge machine. After this the specimens were placed on a refractory brick along with graphite rods and then placed in the microwave cavity. Metallic material cannot absorb microwaves directly and sparking takes place if exposed to microwaves. But, with the help of proper insulation arrangements, it could be made possible for the metallic materials to absorb microwaves. Earlier, MHH was carried out by the use of charcoal as a susceptor material. In this study charcoal was not used, but the use of graphite rods helped the joining to take place. Graphite absorbs microwaves to a great extent thereby producing sufficient heat energy which is conducted to the specimen very quickly because thermal conductivity of graphite is very high. When the base alloy reaches an optimum temperature, it starts absorbing microwaves directly and then joining takes place when the alloy reaches its melting temperature. Since charcoal was not used, there was no need to use the separator; hence graphite sheet was also eliminated.

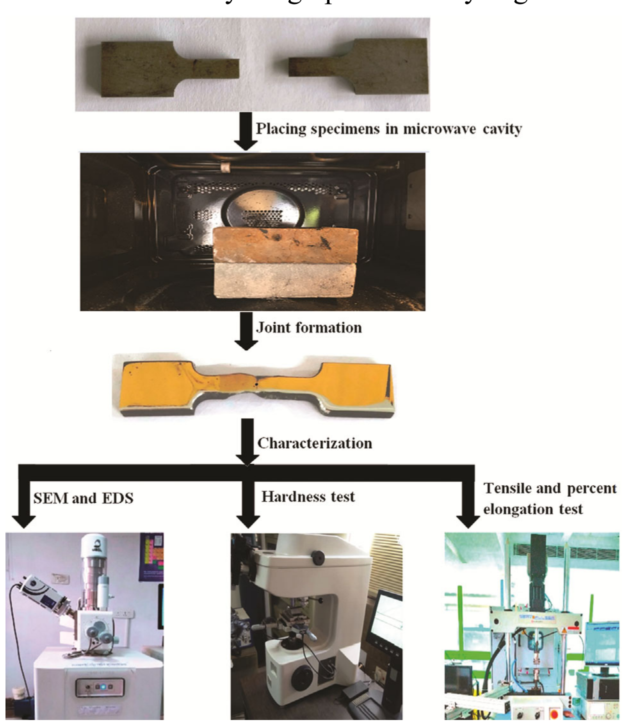


Fig. 1 — Methodology adopted.

Inconel 625 was selected for joining through MHH. Inconel 625 is used in many industries such as aerospace and marine. Chemical composition of the alloy used is shown in Fig. 2. EDS analysis was done to find out the composition of the alloy. Graphite rods were used as susceptor material. Silica brick was used as an insulating material. Cavities were prepared inside silica brick to place the specimen and the graphite rods. Alumina brick was used as a refractory material and was placed on the top of the silica brick to cover the specimen and graphite rods. Alumina brick not only act as an insulating material but also help in avoiding the sparking which takes place if the specimen is directly exposed to the microwaves. Experiment was conducted in a 900 W microwave applicator. The frequency of microwaves used was 2.45 GHz. Frequency of the microwaves play a very important role in joining process because the penetration depth of the microwaves varies inversely with frequency. The penetration depth of microwaves is a matter of concern because more the penetration depth more is the microwave absorption capability of the material and lesser is the time taken by the material to be joined. But microwave applicatorwork at 2.45 GHz and waves of such high frequency cannot be absorbed by the metallic materials directly. Instead, when microwaves of such high frequency fall on the metallic materials, they get reflected. This reflection is so spontaneous and at large scale that sparking takes place in the oven. This sparking can damage the magnetron of the microwave oven. So, to avoid this sparking and help the specimen to absorb microwaves, all the above-mentioned arrangements are done.

The specimens as well as the graphite rods were accommodated in the cavity made inside the silica brick. Six graphite rods were used for focusing heat at the interface. Fig. 2 shows the schematic of the top view of silica brick accommodating the specimen and graphite rods. Size of the graphite rods used during this work was 2 mm diameter and length of the rod was 50 mm. The rods were kept at 45^o to each other and were located as shown in Fig. 3. Six graphite rods were used as susceptor during this work. Silica brick is very soft and brittle. Cavity making in this brick is

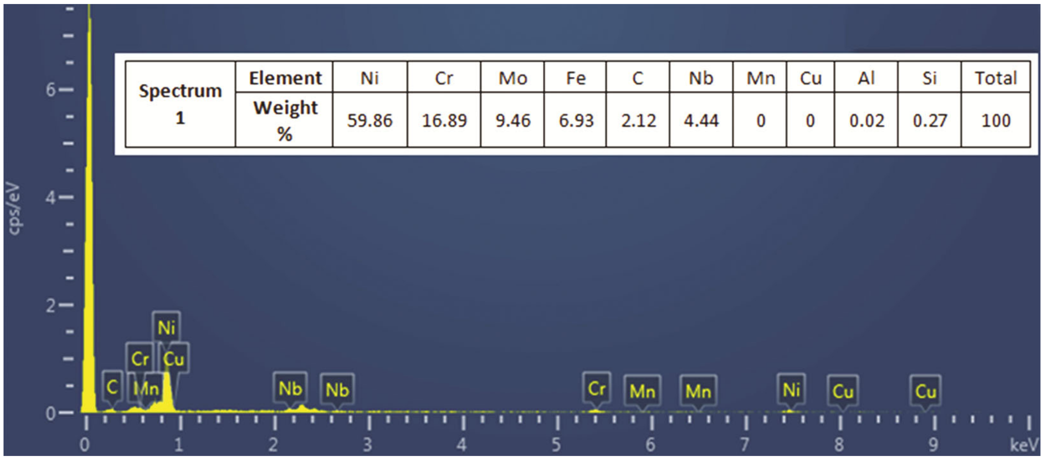


Fig. 2 — Image of the EDS of the original specimen.

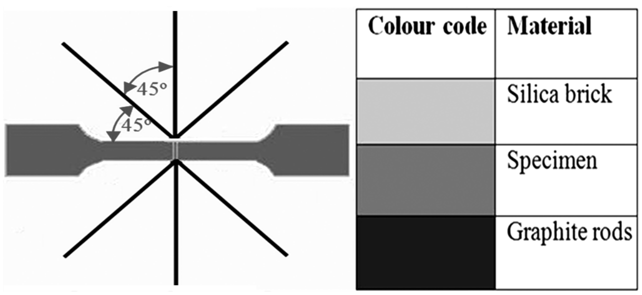


Fig. 3 — Schematic of the top view of the silica brick.

very easy, so specimen and graphite rods can be easily lodged inside this brick [13]. It also acts as a very good insulator hence, helping in retaining the heat generated at the interface. Alumina blocks were used for insulation and also for masking purpose. As soon as the microwave is switched on, a spark is generated inside the cavity where graphite rods meet. This sparking is attributed to the jumping of electrons from one rod to another.

Graphite rods start conducting heat to the alloy interface and soon the critical temperature of the alloy is reached when it starts absorbing microwaves itself and then melting of the alloy takes place at the interface. This whole process was carried out at three different process timings, which are 320, 340 and 360 s. Trial experiments revealed that at 320 s process time, interface region did not melt at all. There was little joining observed at 340 s. Successful joints were fabricated by keeping the process time at 360 s. Present work reports about joints fabricated at 360 s process time.

3 Results and Discussion

In this study, specimens of Inconel 625 were joined without any filler powder, with the help of MHH. After joining, the specimens were subjected to physical as well as mechanical characterization. Physical characterization included SEM and EDS and, mechanical characterization included microhardness and tensile and percent elongation tests. SEM and EDS tests were conducted after polishing the joined specimens and then applying the etchant on the surface. Vickers microhardness tester was utilized for 10 s and the load applied was 50 g for every specimen. The tensile testing was done at a uniform strain rate of 0.01 mm/s under 5 kN load cell.

After joining, the joined specimen was prepared for SEM. Preparation of the specimen is important because it is impossible to see the welded zone and grains of different portion of the welded specimen if the specimen is not polished properly. A reference dot (RD) can be seen in Fig. 4 (a). RD is marked on the joined area because it was difficult to differentiate between the joint and the base alloy since fusion took place very well. RD is taken in the middle of the joined specimen as shown in Fig. 4 (a). Also, a zoomed in image of the joint region is shown in Fig. 4 (b). EDS is taken at the joint area (marked as spectrum 1) which is shown in Fig. 5. Comparison of Figs 2 and 5 shows that there is an increase in chromium as well as carbon content which results into increased hardness of the joint region as compared to the base alloy. This observation is further supported by microhardness-based results presented in next section.

Microhardness testing involves a diamond indenter which is applied to make an indentation on the specimen by application of a certain amount of load. Optical microscope was used to measure the size of the indentation because the size of the indentation is very small in case of microhardness. Hardness is calculated in terms of the mean stress which is applied below the indenter. Initially microhardness was employed for small-size components such as watch gears and foils only but later on it was also extended to many other applications in different research studies also [17]. Mostly pyramidal type indenter is preferred which produces square impression on the specimen. Test loads generally vary from 1-100 gf in microhardness testing. The time period generally taken for the application of the load is 10-15 s. There is a need of careful observation and control over the load in this testing. Before testing the specimen for microhardness, it should be well polished to make it scratch free and also to make the plane of the specimen exactly perpendicular to the axis of the indenter. Vibration free environment is required for testing the specimen for microhardness. The main factors which distinguish microhardness from macrohardness tests are size of the indenters, amount of the load applied and the types of tests used. For instance, microhardness test is conducted using small indenters as compared to the macrohardness test. Lower amount of load is applied in microhardness test which helps to test thinner sheets accurately as compared to the macrohardness test. Vickers hardness test and Knoop hardness test are two of the most popular tests used to measure the microhardness of the material. While macrohardness test is conducted using mostly Brinell hardness test and Rockwell hardness test.

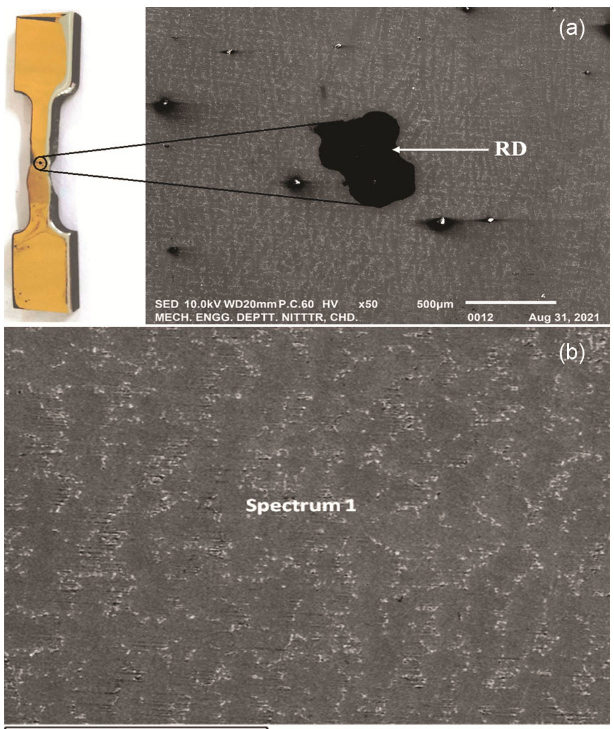
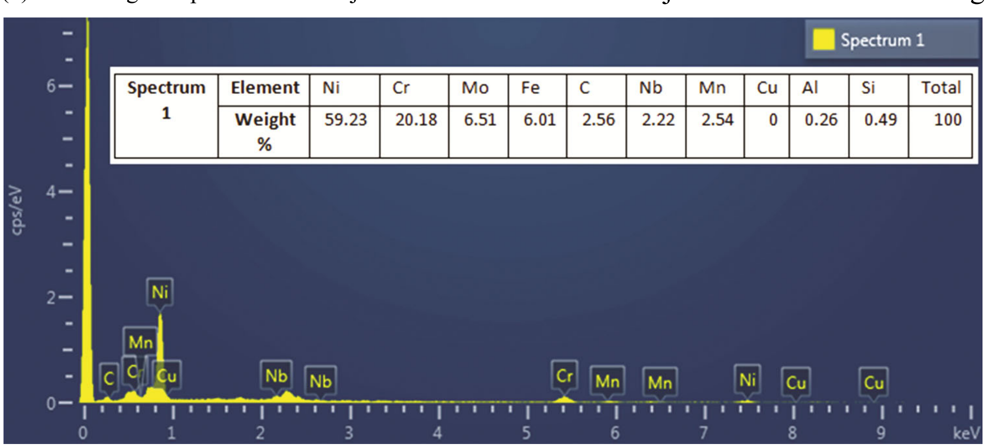


Fig. 4 — (a) Joined specimen with SEM image of the joint zone showing RD, and (b) SEM image of spectrum 1 at the joint.

Three repetitions were done for joining specimens with same parameters and tested individually for microhardness for averaging purpose. It was observed that the average microhardness of three specimens was 325.1 HV and the average microhardness value of the base alloy was 294.7 HV. This implies that the average microhardness of the joint is more than that of the base alloy. The average microhardness at the joint region came out to be 10.32 % more than that of the base alloy. Microhardness results of the present study were compared with some of the previous studies also. In some previous studies [13,15] authors joined Inconel 625 specimens through MHH. Specimens were joined with the help of filler powder. Slurry of nickel-based powder was prepared with the help of Bisphenol-A and Blumer 1450XX and applied at the interface surfaces of the specimens to be joined. Successful joints were made using charcoal as



Spectrum 1	Element	Ni	Cr	Mo	Fe	C	Nb	Mn	Cu	Al	Si	Total
	Weight %	59.23	20.18	6.51	6.01	2.56	2.22	2.54	0	0.26	0.49	100

Fig. 5 — Image of the EDS of spectrum 1 of the joint region.

susceptor and graphite sheet as separator. After the formation of joints physical and mechanical characterization was done. It was revealed through microhardness tests that the average microhardness of the joint is 360 HV and 245 HV respectively[13,15]. Thus, it is observed that microhardness-based results obtained during present work are better than one of the previous published results and almost similar to that of the other study done by other researchers.

After the microhardness testing, the tensile strength was also evaluated experimentally using tensile testing machine. ASTM E-8 standards were used for tensile testing of Inconel 625 specimens. The specimens were cut according to the ASTM E-8 standards through wire electric discharge machining. The tensile testing was done at a uniform strain rate of 0.01 mm/s under 5 kN load cell. The value of the mean ultimate tensile strength of the joined specimens came out to be 319.9 MPa with 5.3% average percent elongation. In previous studies [18] authors joined specimens of Inconel 625 of dimensions 55x10x6 mm^3 through MHH. Filler material was also used in joining process. Flux along with graphite was used as separator in the previous mentioned study. After the formation of joints, characterization was done. In tensile tests it was disclosed that the mean ultimate tensile strength of the joint is 271.81MPa. So, it was observed that the average tensile strength results of the present research (319.9 MPa) are better than results found in previous study (271.81 MPa) done by other researchers. The tensile strength of the original Inconel 625 specimen was also tested and it came out to be 590.48 MPa with elongation of 9.96 %. It is clear that the joint strength as well as the ductility of the joined specimen is lesser than the original base alloy which also inspires for further investigations into the joining process so that better joint strength and ductility can be achieved.

4 Conclusion

It is evaluated from the above study that Inconel 625 can be successfully joined without any filler powder with the help of MHH. Following conclusions can be drawn from this research work:

- A novel process has been developed to join the alloy. In this novel process graphite rods played an important role in the joining of Inconel 625 through MHH.
- Presence of graphite rods helps in concentrating the heat at the interface, this leads to melting of the interface part only thereby resulting in small heat affected zone.
- Joining of Inconel 625 has never been performed without filler material through MHH. But in this work no filler material has been used to join Inconel 625 Instead, the use of graphite rods is sufficient to melt the alloy at the interface which led to the joining of the specimen. It is concluded that not using filler material reduced the cost of joining drastically. Three joints have been has successfully made through this novel process using same parameters.
- The average value of Vickers microhardness recorded at the joint region is 325.1 HV. This value of the microhardness is more than the base alloy. Base alloy exhibits 294.7 HV of average microhardness. So, the value of average microhardness at the joint is 10.32% higher than that of the base alloy, which is expected mainly due to presence of excess amount of chromium at the joint and addition of carbon into the joint region from graphite rods present near the interface of the specimens.
- The value of the mean ultimate tensile strength of the joined specimen is 319.9 MPa with 5.3% average elongation. The value of tensile strength of the original specimen came out to be 590.48 MPa with elongation of 9.96 %. So, it is concluded that the value of the average tensile strength and percent elongation of the welded specimens is less than that of the original specimen. But, as compared with recent researches, the results are satisfactory.
- SEM images show that proper fusion took place at the interface and well fused joints have been made. Also, through EDS spectrum taken at the joint zone it is concluded that chromium and carbon percentage has increased in the joint region, which justifies the increase in hardness at the joint region.

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