State Of Art : Joining Of Microwave Processed Materials

Prateek Gupta, Sudhir Kumar and **Ajay Kumar**
Noida Institute of Engineering and Technology, Greater Noida - 201 306, UP
Corresponding Author's E-mail : s_k_tomar02@yahoo.com

ABSTRACT

Microwave processing is relatively advanced and unfamiliar technique of joining metals and ceramics. Microwave energy has been effectively used in the processing of different materials. It has been introduced in the field of manufacturing and design due to its various advantages over other welding/joining techniques such as – short heating time, hybrid heating, saving energy etc. Microwave heating leads to generation of inverted temperature profile and provides selective heating and as well as volumetric heating. Joining of bulk pieces of similar/dissimilar metals which have high thermal conductivity is really challenging. Microwave processing has numerous advantages over traditional methods of heating. It has been commonly used in various industrial, scientific and medical applications for processing, drying and heating. In the past years, various works has been done on polymers, ceramics except metals by using microwave radiations. Many initiatives have been taken to explore this advanced and emerging technique in various fields of engineering.

1.0 INTRODUCTION

The word microwave is not relatively new in the human lives because there are million's of microwave ovens in households all across the world. It has great success in field of processing food but people believes that microwave technology can also be wisely employed for processing materials because it improves the physical properties of the materials. Due to volumetric heating, a more rapid heating is done in comparison with the conventional heating process. Heat is generated internally within the material, instead of originating from the external sources and gets transmitted outward. Hence, there is an inverse heating profile, 'inside-out' unlike in a conventional heating 'outside-in'. Osepchuk has explained the basics of microwave heating and presented a brief history of the applications of microwave energy [1]. Later, the same author explored the possible areas of applications of microwave power in details [2]. Significance of microwave heating and its applications in processing of ceramics were then analyzed by Sutton in a landmark publication in 1989 [3]. The unique features of processing materials with microwave were lucidly presented. Later, Clarke et al. have shown the potentials and challenges of using microwave energy in materials processing [4]. Subsequently, application of microwave energy in material processing was reported in many areas including the new and unusual application like glazing of sprayed ceramic composite surfaces [5]. Various characteristics, which are not available in the conventional processing of materials, are selective heating of materials, penetrating radiations etc. Joining of dissimilar material is more challenging than the similar due to different mechanical properties and chemical compositions. The microwave-metal interaction is quite different than that of ceramics because no internal electric field is induced in the metals, as metals are good electrical conductors. In microwave processing, volumetric heating takes place due to the generation of electromagnetic waves from the microwave which converts into heat ~ 100 %. Microwave processing of materials have several advantages over the conventional heating like improved product yield, unique microstructure and properties etc. It provides large amount of saving in terms of energy.

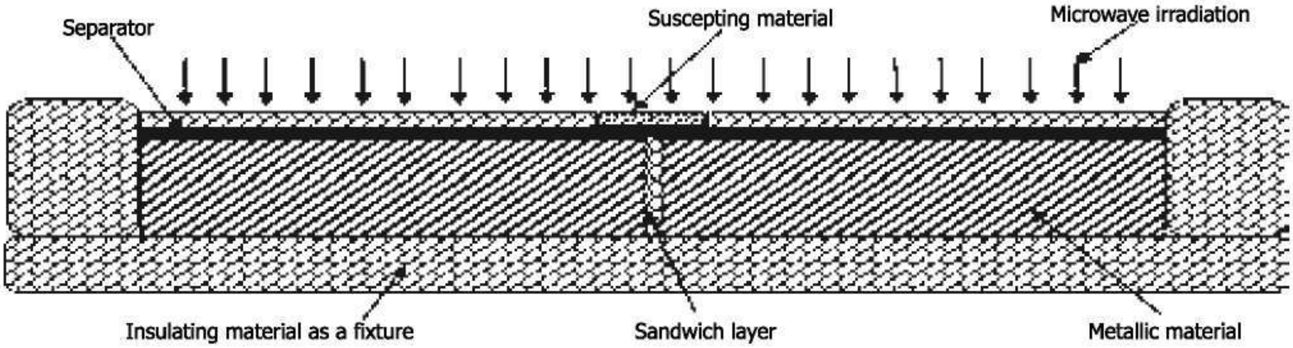


Fig. 1 : Schematic of microwave hybrid heating process for joining of metallic copper [6].

This creates an opportunity to utilize the advantages of microwave energy for processing of metallic material to meet the challenging and growing needs in many industrial applications. **Fig. 1** shows schematic arrangement of microwave joining of metals.

2.0 LITERATURE REVIEW

Aravindan and Krishnamurthy [6] explained that ceramic matrix composites which were use in high technology applications because of their enhanced toughness and wear resistance. Reliable joining techniques are needed for the development of intricate shapes made of ceramic composites. In this present work, sintered alumina–30% zirconia ceramic composites were joined by hybrid heating using microwave radiation (45 GHz, 700 W) along with sodium silicate glass powder as an interlayer. The joints/welds were studied using XRD, SEM, EPMA, microhardness, and 3 point bend tests. **Figure 2 (a, b &c)** presents the frozen layer of glass at the welded interface, crystalline and platelets of frozen glass at the interface and wavy texture of ceramic composites [7].

Sharma et al. observed that atmospheric plasma sprayed ceramic composites can be widened considerably by reducing/reliminating inherent surface defects by treating them through techniques like microwave irradiation. Ceramics are transparent to microwaves at low temperatures, however, start absorbing microwaves at higher temperatures resulting change in microstructure and material characteristics. Sharma et al. presents microwave processing of atmospheric plasma sprayed alumina–titania ceramic composite coatings in conventional microwave heating system and evaluation of the processed materials through XRD, SEM, microhardness survey and surface finish. Results indicate that microwave irradiation induces densification of the material and possible flow of dominant gamma-alumina phase that leads to glazing of coated surface. Glazed surfaces exhibit enhanced microhardness as well as surface finish. **Fig. 3 (a, b & c)** shows scanning electron micrograph of glazed surface, scanning electron micrograph as-sprayed surface texture and Typical layered structure of plasma sprayed coatings —sectional view [8].

(a) (b) (c)

Fig. 2 (a, b & c) Typical frozen layer of glass at the weld interface, Crystalline and platelets of frozen glass at the interface and Wavy texture of ceramic composite due to the martensitic transformation of Zirconia [7].

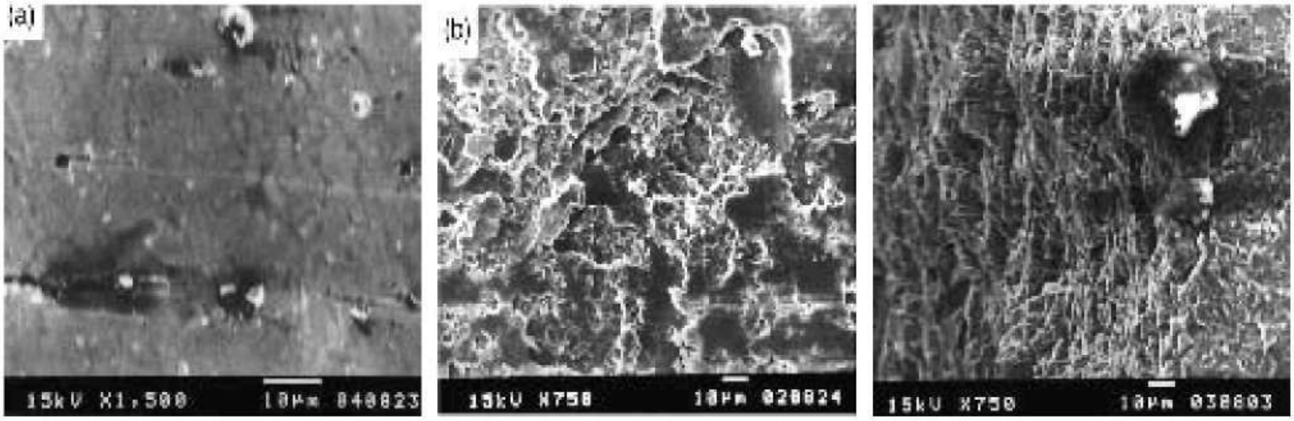


Fig. 3 (a, b & c) : Scanning electron micrograph of glazed surface, scanning electron micrograph as-sprayed surface texture and typical layered structure of plasma sprayed coatings—sectional view [8].

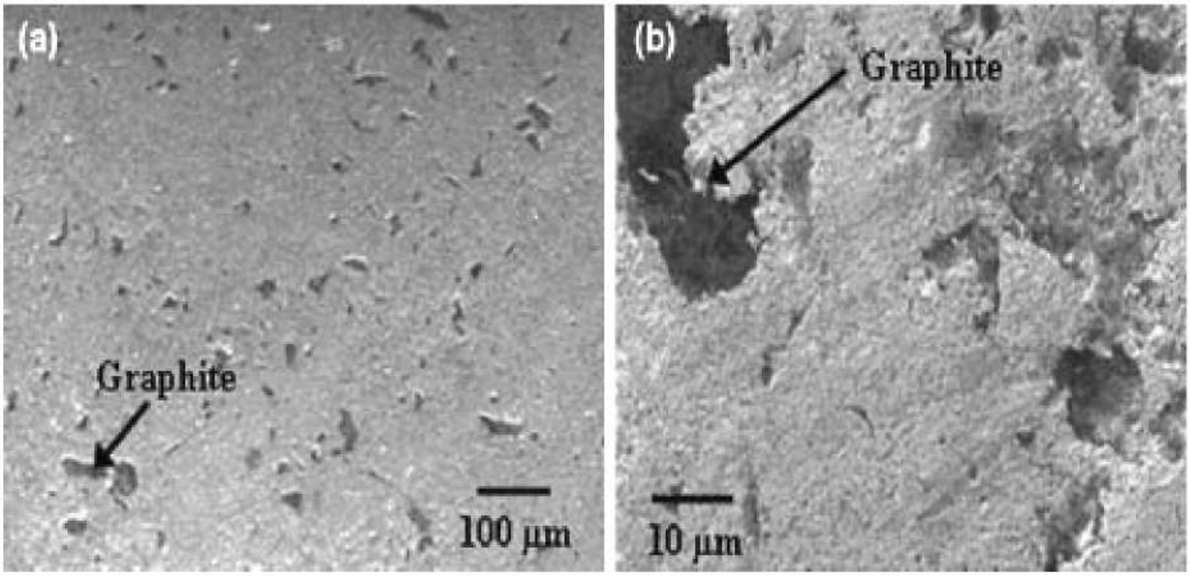


Fig. 4 (a, b) : SEM image of copper-graphite composite [9].

Rajkumar et al. concluded copper-graphite composite is an important tribological material used in electrical sliding contact applications like electrical brushes in motors and generators. Accelerated wear testing was carried out to evaluate the life characteristics of the composite. This work focuses on evaluation of tribological performance of microwave-sintered copper-graphite composite using accelerated wear testing methodology using high temperature pin-on-disc tribometer. Microstructural studies of worn out surfaces were carried out using SEM with EDAX. Reliability and analysis on life characteristics were performed on the time-to-failure data using temperature-nonthermal-accelerated life-stress model. The life of the composite obtained through testing at mean and 99% reliability are 18,725 and 16,950 h, respectively [9].

Bajpai et al. observed the development of natural fiber reinforced polymer composites, has received widespread attention due to their environment friendly characteristics over the synthetic fiber based polymer composites. In the current article, natural fibres (nettle and grewia optiva) reinforced polylactic acid green composites and joint strength has been evaluated in each case as per standard procedures and results showed that microwave joining provides higher joint strength as compared to adhesive bonding. The results of the experimental study are in close agreement with the finite element investigation [10].

Metaxas and Meredith reported that microwaves were part of the electromagnetic spectrum with the wave-length ranging from 1 m to 1 mm, which corresponds to a frequency range of 300 MHz to 300 GHz. The most commonly used frequencies for domestic and industrial heating purposes are 915 MHz and 2.45 Ghz. These frequencies correspond to significant penetration depth within most of the materials and hence are

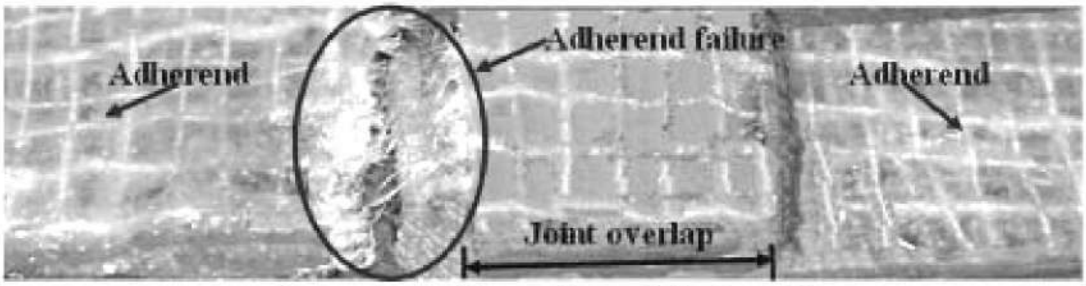


Fig. 5 : Adhesive failure under tensile loading [10].

suitable for most laboratory reaction conditions [11]. Microwaves can be generated by a variety of devices such as magnetrons, klystrons, power grid tubes, travelling wave tubes, and gyrotrons but the most common source is the magnetron which is more efficient, reliable, and available at lower cost than other sources [12].

Microwaves possess several characteristics with unique features that are not available in the conventional processing techniques. The use of microwave energy to process a wide variety of ceramics and ceramic composite materials offers many new opportunities [13]. Microwave processing of ceramics is an emerging technology in which the energy is applied directly to the material, enabling rapid and efficient sintering [14]. The process shows potential for the synthesis of advanced structural and functional ceramic materials with superior properties unattainable by other means [15]. This is a complex process involving the propagation and absorption of electromagnetic waves in the ceramic materials, heat transport within the geometric body and densification of the materials [16].

Ahmad and Siores studied that microwave heating leads to generation of an inverted profile and provide selective heating with ceramic. With rising temperature, however, most ceramics became increasingly susceptible to microwave energy. Thorough studies have been conducted to characterise zirconia-alumina-silica ceramics at high temperatures. Time temperature behaviour of alumina-zirconia-silica ceramics at different power has also been studied. On-line load matching techniques using six-port impedance analyser coupled to a motorised three-stub tuner, have been utilised to optimize power transmission and energy deposition rates to the materials. Microwave joining trials of alumina-zirconia-silica and high purity alumina ceramics have yielded joint strengths in excess of the base metal strength. Moreover, impure interlayer's between mating surfaces, which tend to decrease joint strengths, have been totally eliminated. **Fig. 6** shows Time-Temperature characteristics for zirconia- alumina- silica ceramics heated at varying microwave power [17].

Gupta and Wong reported the two-directional microwave assisted rapid sintering of aluminum, magnesium and lead free

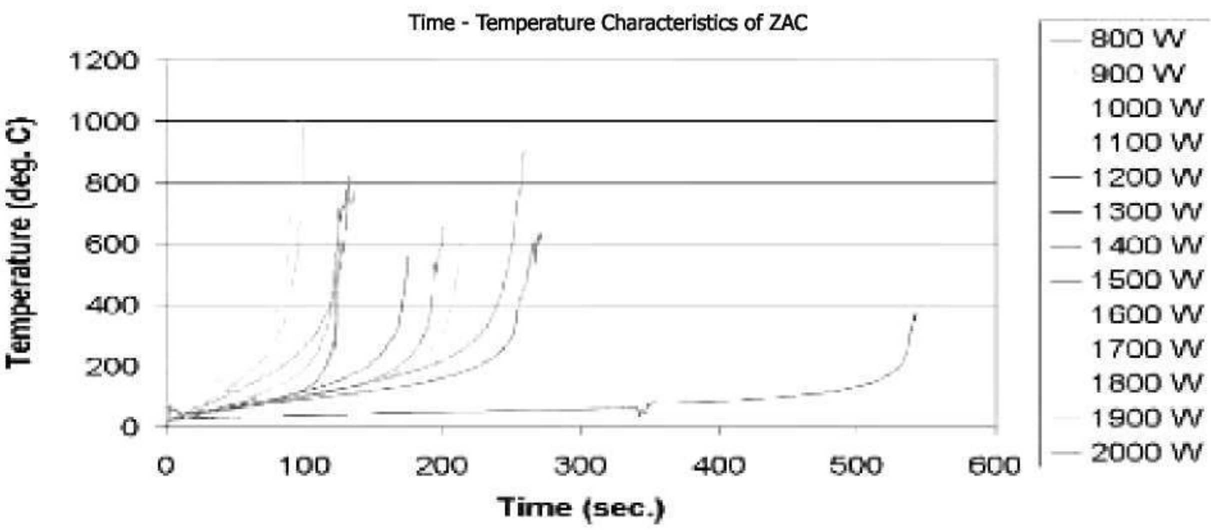


Fig. 6 : Time - Temperature characteristics for ZAC heated at varying microwave power [17].

solder. The results revealed that the density of the microwave sintered and conventionally sintered samples are same whereas the marginal increase in microhardness with superior ultimate tensile strength of the microwave sintered aluminum and magnesium [18].

Prabhu et al. examined the comparative sinterability of as received powder and activated tungsten powder in microwave. It was observed that the activated tungsten powder shows better densification because of reduced particle size and higher specific surface energy [19]. Mondal et al. exposed different particle sized electrically conductive material like copper having varied initial porosity. The reported results indicate that the smaller the particle size with higher porosity, the higher will be the microwave absorption rate. Hence, heating is rapid [20].

Braze powder was used as interface layer with microwave temperature upto 1000°C. In continuation of the previous study, Sallom et al. reported the brazing of Gamma TiAl with Ag-based filler metal by microwave heating between 925°C to 1050 ° C in 5 min with 1 MPa load [21]. Budinger presented brazing of nickel based superalloys with nickel based metallic powders in a multimode microwave cavity [22].

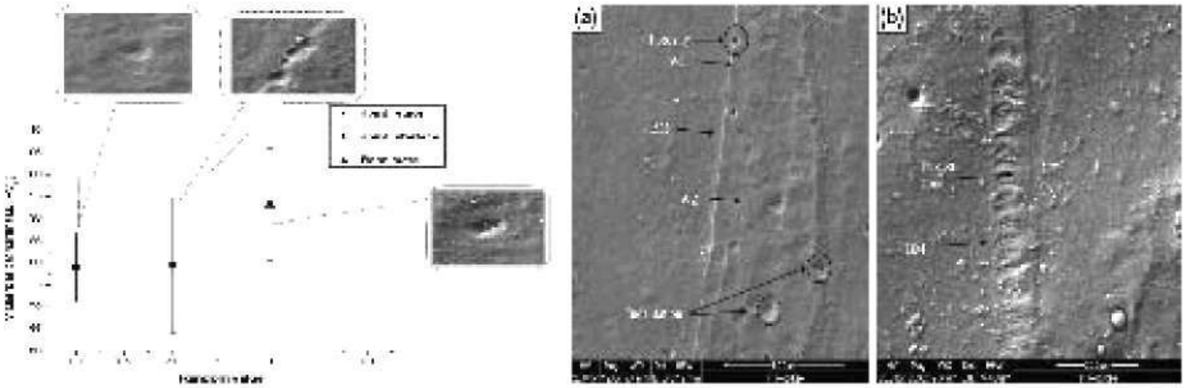
Lei et al. concluded microwave-based bonding of polymer substrates is a promising technique for achieving precise, localized and low temperature bonding. One of the advantages of the process is that polymethyl-methacrylate (PMMA) is relatively transparent to microwave energy in the 2.4 GHz regime. This makes, it an excellent substrate material for microwave bonding. Selective heating and melting of the thin layers of metal also causes localized melting of the PMMA substrates and improves adhesion at the interface. Results show that~ 1m of interfacial layer can be generated that is composed of the melted gold and PMMA, and which can hold two substrates together under applied tension greater than 100 lb/in.2 (7 kg/cm^2). A numerical simulation was also performed and validated with experimental results to show that globally the PMMA substrates indeed remained below its melting point during the microwave bonding process [23].

Recent research activities, however, indicate that it is possible to process metals under certain conditions many commercial powder metal components and their alloys have been sintered using microwaves. It has been reported that the powders with a composition of iron (Fe), copper (2%) and graphite (0:8%) have been sintered in a microwave field at 1200℃ for 30 min with excellent density [24].

Roy et al. reported microwave application in material processing yields very fast and clean processing. However, application of microwaves for metallic material processing is a challenging area of research owing to reflection of electromagnetic waves by most of the metals at ordinary conditions. Recent literature has shown very limited research in the area of metallic material processing in the form of sintering under certain conditions [25–28]. Further, work has been reported in brazing of selected metals under specific conditions [29, 30]. Joining of bulk metallic materials in different forms in a home microwave system has also been reported [31, 32]. However, cladding/coating of metallic and non-metallic powders on metallic substrates has been reported in the form of patent [33].

Srinath et al. observed that microwave joining of stainless steel (SS-316) to mild steel (MS) in bulk form has been successfully carried out using a multimode applicator at 2.45 GHz and 900 W. A nickel based metallic powder was used as a sandwich layer between the bulk pieces. Resulting joints were characterized using field emission scanning electron microscope (FESEM), X-ray diffractometer, microhardness tester and universal testing machine. Microstructure study showed the faying surfaces were well fused and got bonded on either side of the base material. The average observed Vickers' microhardness of core of the joint area was observed to be 133 Hu with 0.58% porosity. The ultimate tensile strength of the joint was found to be 346.6 MPa with percentage elongation of 13.58% [34].

Srinath et al. studied that metallurgical joining of high thermal conductivity materials like copper has been technically challenging. Joining of copper in bulk form has been carried out using microwave energy in a multimode applicator at 2.45 GHz and 900 W. Charcoal was used as susceptor material to facilitate microwave hybrid heating (MHH). Copper in coin and plate forms have been successfully joined through microwave heating within 900 s of exposure time. A sandwich layer of copper powder with approximately 0.5 mm thickness was introduced between the two candidate surfaces. Characterisation of the joints has been carried out through microstructure study, elemental analysis, phase analysis, microhardness survey, porosity measurement and tensile strength testing. X-ray diffraction (XRD) pattern indicates that some copper powder particles got transformed into copper oxides. A dense uniform microstructure with good metallurgical bonds between the sandwich layer and the interface was obtained. The hardness of the joint area was observed to be 78 ± 7 Hu, while the porosity in the joint was observed to be 1.92%. Strength character of the copper joints shows approx. 29.21% elongation with an average ultimate



(a) (b)

Fig. 7 : (a, b): Vickers microhardness profile at various zones and SEM micrograph of the copper joint [35].

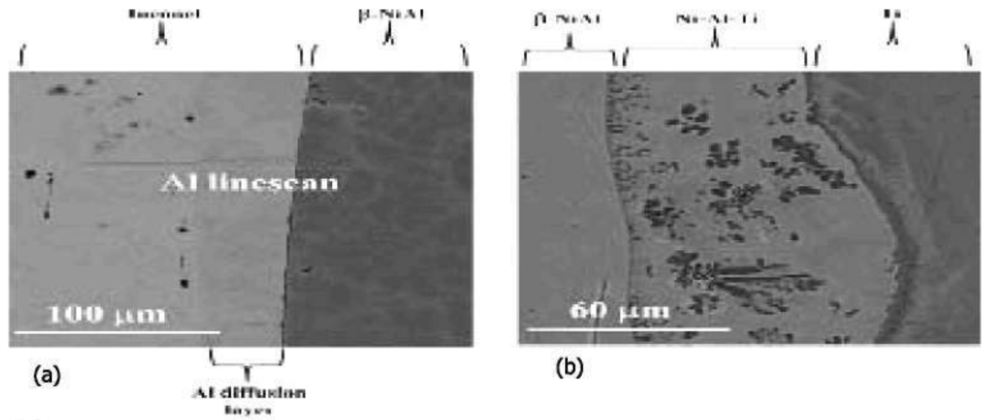


Fig. 8 (a, b): Interface between CSed b-NiAl and Inconel substrate; EDS Al line scan across [36]

tensile strength of 164.4 MPa. **Fig. 7 (a, b)** presented the Vickers microhardness profile at various zone and SEM analysis of copper [35].

Rosa et al. reported microwave energy has been exploited to ignite combustion synthesis (CS) reactions of properly designed powders mixtures, in order to rapidly reach the joining between different kinds of materials, including metals (Titanium and Inconel) and ceramics (SiC) **Fig. 8 (a, b).** In case of microwaves absorbing substrates, the competitive microwaves absorption by substrates and powdered joining material, leads to the possibility of adhesion, interdiffusion and chemical bonding enhancements. In this study, both experimental and numerical simulation results are used to highlight the great potentialities of microwave ignited CS in the joining of advanced materials [36].

3.0 FUTURE SCOPE OF WORK

Microwave welding has advanced in the new techniques of welding and it is not fully explored yet. Very few work has been done regarding joining of metals by microwave welding. No researcher has studied the effect of particles size of sandwich material, load applied on work pieces, position of work pieces etc. Nobody has done mathematical modelling using any optimization techniques. So, there is lot of scope to do the research in the field of metals microwave welding.

4.0 CONCLUSIONS

Ceramics and composites are joined successfully under electromagnetic waves. Joining of metals is really difficult due to their reflective nature of electromagnetic waves. Joining of similar metals like copper is joined at 900 W and 2.45 GHz frequency. The joint is characterized using XRD, SEM, Microhardness, tensile strength and % elongation. Microstructure shows that very less porosity is observed and no cracks are visible. Microhardness, tensile strength and % elongation of the joint are 78 ± 7 Hu, 164.4 MPa and 29.21 % respectively. Dissimilar metals are also joined using Ni based powder as an interfacing material in microwave processing. Due to the reflective nature and high thermal conductivity of the metals, joining of metals is really difficult and challenging.

This process is not fully developed. Further research effect in the field and better understanding of the process characteristics can pave the way for the commercial success of this technology as well.

REFERENCES

1. Osepchuk John M., (1984); A history of microwave heating applications, IEEE Trans Microwave Theory Technology, 32(9), pp. 1200–1224.
2. Osepchuk John M., (2002); Microwave Power applications, IEEE Trans Microwave Theory Technology, 50(3), pp. 975–985.
3. Sutton W. H., (1989); Microwave processing of ceramic materials, American Ceramics Society Bulletin, l68, pp. 376–386.
4. Clark D. E., Sutton W. H. and Lewis D., (1996); Microwave processing of materials, Annual Review Material Science, 26, pp. 299– 301.
5. Sharma A. K., Aravindan S. and Krishnamurthy R., (2001); Microwave glazing of alumina- titania ceramic composite coatings, Material Letters, 50, pp. 295–301.
6. Srinath M. S., Sharma Kumar Apurbba and Kumar Pradeep, (2011); A new approach to joining of bulk copper using microwave energy, Materials and Design, 32, pp. 2685–2694.
7. Aravindan S. and Krishnamurthy R., (1999); Joining of ceramic composites by microwave heating, Materials Letters, 38, pp. 245–249.
8. Sharma A. K., Aravindhan S. and Krishnamurthy R., (2001), Microwave glazing of alumina–titania ceramic composite coatings, Materials Letters, 50, pp. 295–301.
9. Rajkumar K., Aravindan S. and Kulkarni M. S., (2012); Wear and Life Characteristics of Microwave-Sintered Copper-Graphite Composite, Journal of Materials Engineering and Performance (in press).
10. Bajpai Kumar Pramendra, Singh Inderdeep and Madaan Jitendra, (2012); Joining of natural fiber reinforced composites using microwave energy: Experimental and finite element study, Materials and Design, 35, pp. 596–602.
11. Metaxas A. C. and Meredith R. J., (1983); Industrial Microwave Heating, London: Peter Peregrinus, UK.
12. National Research Council, (1994); Microwave Processing of Materials, New York: National Academy Press.
13. Sutton W. H., (1993); Microwave processing of materials, MRS Bull. 18(10), pp. 22.
14. Sutton W. H., American Ceramics Society Bulletin, 68, pp. 376.
15. Birnboim A. and Carmel Y., (1989); Journal American Ceramics Society, 82(11), pp. 3024–3030.
16. Calame J. P., Birman A. and Carme Y. L., Gershon D., Levush B., Sorokin A., Senov V. E., Dadon D., Martin L. P. and Rosen M. , (1996); Journal Applied Physics, 80(7), pp. 3992–4000.
17. Ahmad Ammar and Siores Elias, (2001); Microwave joining of 48% alumina-32% zirconia-20% silica ceramics, Journal of Material Processing Technology, 118, pp. 88-95.
18. Gupta M. and Wong W. L. E. , (2005); Enhancing overall mechanical performance of metallic materials using two-directional microwave assisted rapid sintering, Scripta Mater, 52, pp. 479–483.
19. Prabhu G., Chakraborty Amitava and Sarma Bijoy, (2009); Microwave sintering of tungsten, International Journal of Refractory Metals and Hard Materials, 27, pp. 545–548.
20. Mondal Avijit, Agrawal D. K. and Upadhyaya Anish, (2009); Microwave heating of pure copper powder with varying particle size and porosity, The Journal of microwave power and electromagnetic energy, 43(1), pp. 5–10.
21. Sallom Z. K., Akselsen O. M. and Zhang J., (2005); Brazing of gamma TiAl with Ag based Filler metal, Euro mater, pp. 1–30.
22. Budinger David Edwin, (2008); Microwave brazing process, US Patent; 0290137.
23. Kin Fong Lei, Syed Ahsan, Nasser Budraa, Wen J. Li and John D. Mai, (2004); Microwave bonding of polymer-based substrates for potential encapsulated micro/nanofluidic device fabrication, Sensors and Actuators A 114, pp. 340–346.
24. Rodiger K., Dreyer K., Gerdes T. and Porada Willert M., (1998); Microwave Sintering of Hardmetals, International Journal of Refractory Metals and Hard Materials, 16, pp. 409–416.
25. Roy R., Agrawal D., Cheng J. and Gedevanishvili S., (1999); Full sintering of powdered metal parts in microwaves, Nature, 399, pp. 668–70.
26. Chillar P., Agrawal D. and Adair J. H., (2008); Sintering of

molybdenum metal powder using microwaves energy, Powder Metallurgical, 51(2), pp. 182–7.

27. Mondal Avijit, Agrawal Dinesh and Upadhyaya Anish, (2009); Microwave heating of pure copper powder with varying particle size and porosity, Journal of Microwave Power Electromagnetic Energy, 43(1), pp. 5–10.

28. Rodiger K., Dreyer K., Gerdes T. and Willert Porada M., (1998); Microwave Sintering of Hardmetals, International Journal of Refractory Metals and Hard Materials, 16, pp. 409–16.

29. Budinger David Edwin, (2008); Microwave brazing process, US Patent. 2008. p. 228119.

30. Barmatz Martin, Jackson W. and Radtke Robert P., (2000); Microwave technique for brazing materials. US Patent, p. 6054693.

31. Siores E. and Rego D., (1995); Microwave applications in materials joining. J Mater Process Technol, 48, pp. 619–25.

32. Sharma A. K., Srinath M. S. and Kumar Pradeep, (2009); Microwave joining of metallic materials. Indian Patent, Application no. 1994/Del/2009.

33. Sharma A. K. and Gupta Dhreej, (2010); A method of cladding/coating of metallic and nonmetallic powders on metallic substrates by microwave irradiation, Indian Patent, Application no. 527/Del/2010.

34. Srinath M. S., Sharma Kumar Apurbba and Kumar Pradeep,(2011); A new approach to joining of bulk copper using microwave energy, Materials and Design, 32, pp. 2685–2694.

35. Srinath M. S., Sharma Kumar Apurbba and Kumar Pradeep, (2011); A new approach to joining of bulk copper using microwave energy, Materials and Design, 32, pp. 2685–2694.

36. Rosa Roberto, Colombini Elena, Veronesi Paolo , Poli Giorgio, and Leonelli Cristina, (2012); Microwave Ignited Combustion Synthesis as a Joining Technique for Dissimilar Materials, Journal of Materials Engineering and Performance, 21(5), pp. 725-732.