Challenges in Microwave Processing of Bulk Metallic Materials and Recent Developments

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Abstract

In the recent years, microwave energy has been exploited for processing of metallic materials through different heating based processes such as sintering, joining, cladding, casting and drilling. Metallic powders are primarily processed through microwave sintering; whereas, other processes are used to heat/melt/ablate desired portion of the bulk metallic materials. Microwave sintering is the most mature process in terms of the literature and its presence in the industry among these processes. The feasibilities of casting, joining and cladding processes are well documented, though they are yet to become popular in industrial applications as alternatives to the conventional processes. Microwave drilling of non-metals have been demonstrated; however, drilling of the bulk metals using microwave energy is in the investigation stage and needs exhaustive experimentation to get established as an advanced metal machining process. This letter provides an overview of microwave energy based techniques used for processing of bulk metallic materials. The challenges in processing these materials have been identified; processing strategies have been briefly discussed. Future research opportunities in microwave processing of the bulk metallic materials have been outlined.

1 Introduction

Microwave processing of the metallic materials was reported in the year 1999 during sintering of metal powders [1]. In the recent years, sintering of different metallic powders was demonstrated worldwide by many research groups [2-8]. However, bulk metallic materials were considered almost inappropriate for microwave processing due to reflection of microwaves from their surfaces at room temperature [9]. The reflected microwaves appear in the form of sparks at the corners of the target material and may cause damage to the magnetron of the applicator. Thus, metallic materials in the bulk form offer higher processing challenges than powders. The area of microwave processing of bulk metallic materials remained unexplored until 2004 and the first report was published in the year 2005 for melting and heat treatment of the bulk metals/alloys [10]. The principles of microwave hybrid heating were used to heat/melt the bulk metals inside the applicator cavity. Melting of different metals/alloys was also reported using microwave energy [11, 12], thermal characteristics of the metals during microwave and conventional melting processes were also reported [12]. In another work, microwave melting of the bulk metals was claimed to be a faster melting process as compared to other conventional processes [13]. Casting of the bulk metallic materials was also demonstrated by drifting the molten metal into a mold cavity. However, these approaches were mostly limited to melting of the bulk metallic materials; microwave casting and cast properties were hardly reported. Recently, a new process known as ‘in-situ microwave casting’ was reported for casting of the metallic materials using microwave energy at 2.45 GHz [14]. It was further reported that use of microwave energy during in-situ casting process affects cast properties significantly [14, 15].

Microwave melting and casting requires complete melting of the bulk metals; however, selective melting requirements in the target materials during approaches such as microwave joining and cladding offer more challenges. Microwave joining necessitates selective melting of the interface metallic powder and candidate layers of the bulk metals. Joining of similar and dissimilar bulk metals/alloys was reported using microwave energy with better joint properties [16-20]. Joining of steel pipes, which is far more challenging than solid materials, was also reported using microwave energy at 2.45 GHz [21]. Microwave cladding requires melting of the clad powder layer placed over the target bulk metal substrate. Cladding of different materials (metal, composites and cermets) were reported on stainless steel (SS) work pieces [22-27].

It was reported that performance of the clad layer improves as structure of the clad powder approaches nano regime from micro size [22, 23]. Each technique, however has its own strength and limitations. It is also a fact that processes do not get matured in the laboratories, applications help identifying the weaknesses and consequently in improving them. Application-wise, microwave processing of metallic materials is still in its infancy. In the present work, an overview of microwave processing of the bulk metallic materials has been presented. The recent developments in the area are discussed. The challenges in the area have been identified and future research directions have been outlined.

2 The challenges

There are many challenges associates with processing of bulk metallic materials using microwave energy due to their unfavourable material properties for microwave coupling and special tooling requirements. Interaction of microwaves with the metallic materials depends upon their skin depth $\delta = 1/ (\pi f \mu \sigma)^{0.5}$, where, f is the frequency of incident microwaves, μ is complex magnetic permeability and σ is electrical conductivity of the material. An induced electric filed is developed inside the metallic material during irradiation due to higher electrical conductivity of the metals and the external field gets suppressed. Thus, almost all incident microwaves get reflected from the metallic surfaces. Another material property is the 'dielectric loss factor' which contributes to microwave heating; it is generally negligible in the metallic materials. Thus, heating effect of microwaves due to electric field reduces in the metallic materials at room temperature. Microwave coupling with the metallic materials; however, gets enhanced as temperature of the target materials reaches beyond a material specific critical value. Therefore, hybrid heating technique is used to elevate the material temperature upto its critical temperature.

Design of tooling for specific processing requirements is another challenge in microwave processing of the bulk metals. Selection of materials to be used as parts of the tooling, and optimum location of the tooling inside the applicator cavity for higher efficiency are some more issues related to the processing of the bulk metallic materials. In the subsequent section, working strategies used in the different processes have been discussed to overcome some of these challenges.

3 Processing strategies

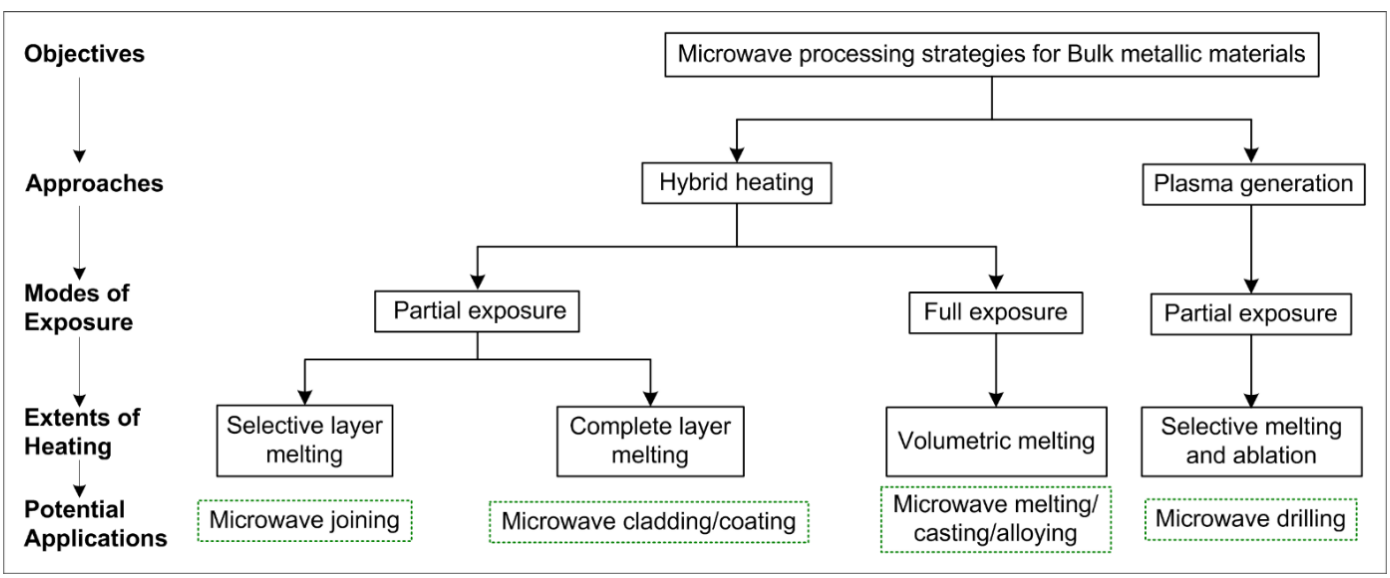

Figure 1: Different processing strategies for bulk metallic materials

Different strategies used for microwave processing of bulk metallic materials are shown in Fig. 1. Generally, hybrid heating technique is used in partial and full exposure mode for different processes. In partial mode of processing, the tooling is designed to allow microwave-metallic material interaction at the desired locations, for example, microwave joining and microwave cladding processes.

The full exposure mode is suitable for melting and casting of the metallic materials using microwave energy. Details of the tooling used in these processes may be found elsewhere [14, 19, 23]. Another strategy for processing the bulk metallic materials is generation of plasma using a monopole for subtractive process such as drilling. In this approach, material is exposed partially and heated selectively beyond the melting temperature of the target metal and ablation of the material takes place from the selected location. Consequently, machining of the target is possible using microwave energy.

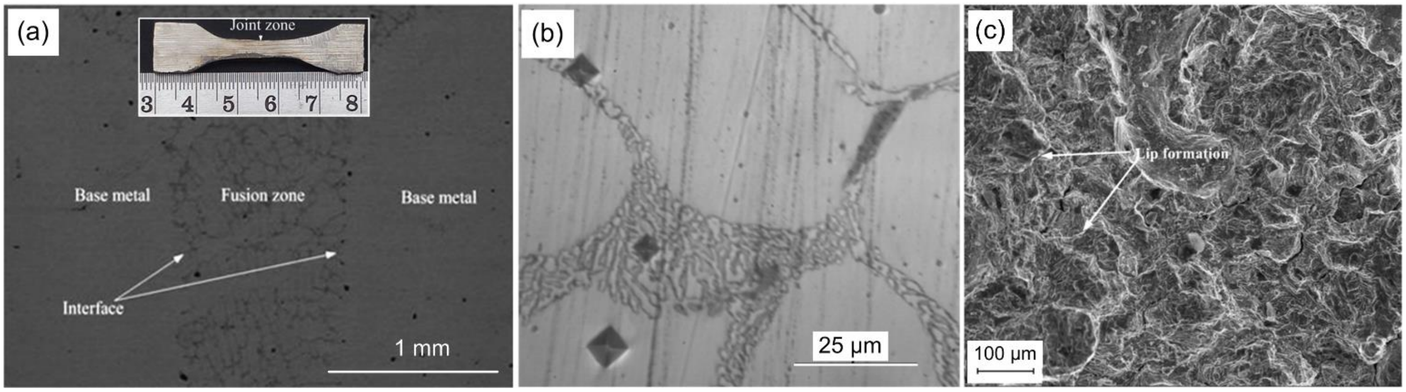

Figure 2: Typical results of microwave joining of Stainless Steel (SS) 316 [18] (a) scanning electron micrograph (SEM) of the joint (insert: typical joint), (b) micro indentation geometries in the joint, and (c) fractograph of the failed joint under tensile loading

4 Notable developments

4.1 Microwave joining

Joining of similar and dissimilar bulk metallic pieces (rod, plates and pipes) using microwave energy at 2.45 GHz has been reported mostly in the present decade [16-21]. Generally, the alloys with higher industrial importance such as mild steel, stainless steel, copper and Inconel were investigated. It was reported that the properties of the joints developed using microwave energy were found comparable with other advanced joining techniques such as laser welding, tungsten inert gas welding etc. [28].

Fig. 2 illustrates developed stainless steel (SS) 316 joint using microwave energy at 2.45 GHz and results of the joint characterization. A typical SS 316 joint is shown in Fig. 2a (insert). Scanning electron micrograph (SEM) of the developed joint indicates dense structure (Fig. 2a). Fig. 2b shows the micro indentation characteristics of the joint. Detailed discussion on the tensile characteristics of the SS joints were presented elsewhere [18]. A mixed mode of fracture was reported in the joint (Fig. 2c) while subjected to tensile loading. Typical results of Inconel-SS joint developed using microwave energy at 2.45 GHz are shown in Fig. 3. The SEM image of the dense joint are shown in Fig. 3a. Micro indentation geometries at the dissimilar joint are illustrated in Fig. 3b. A typical fractured specimen after tensile testing (Fig. 3c) revealed that ductile-brittle mode of fracture occurs in the joint. More details of tensile characteristics of the dissimilar joints were discussed elsewhere [20].

4.2 Microwave cladding/coating

Cladding/coating of the different clad powders (metal, ceramic, cermet and composites) on the bulk metallic materials (mostly on SS) were reported using microwave energy at 2.45 GHz [22-27]. Use of nano size clad powders improves heating rate and offers better properties in the clad as compared to the micro size clad powders [22, 23]. A typical temperature profile of the nano clad powder heated using microwave energy at 2.45 GHz is illustrated in Fig. 4a. Different heating states during microwave nano clad formation are explained in Fig. 4b. A SEM image (insert Fig. 4a) of the developed nano clad indicates presence of finer carbide particles in the clad structure.

Fig. 5 illustrates the nano and micro structured microwave clads. It indicates that use of nano clad powder forms clustering of nano structured grains in the processed microwave clad; whereas, skeleton structured carbides were reported in the microwave clads developed using micro clad powders. It was reported that micro indentation hardness and wear characteristics of the nano structured clad were better than the micro clads [22, 25]

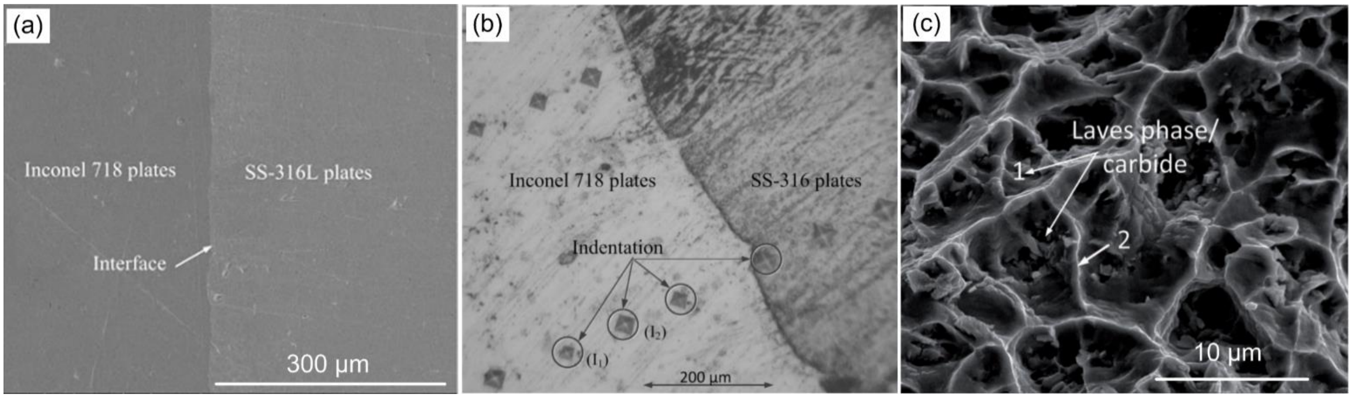

Figure 3: Typical results of microwave joining of Inconel-SS [20] (a) scanning electron micrograph (SEM) of the joint, (b) micro indentation geometries in the joint, and (c) fractograph of the failed joint under tensile loading

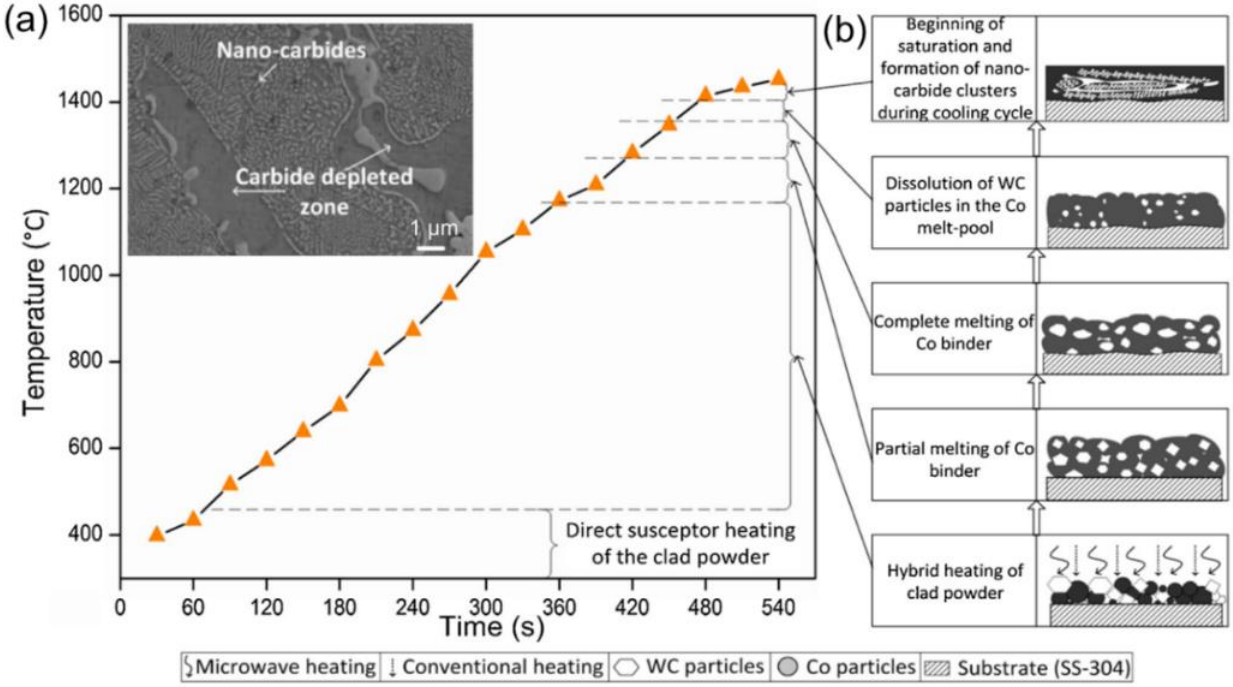

Figure 4: Development of microwave nano clad [23] (a) thermal characteristic of clad powder (inset: SEM image of the nano clad) and (b) mechanism of nano clad development

4.3 Microwave casting

Casting of metallic materials using microwave energy was reported through conventional and in-situ casting approaches. In the conventional approach, the charge is melted using microwave energy and casting (pouring and solidification) is carried out inside a mold placed outside the applicator. On the other hand, melting, pouring and solidification of the target material are accomplished inside the applicator during in-situ microwave casting. Conventional casting limits the use of microwaves upto the melting stage only; whereas, better utilization of microwave energy is possible in the in-situ microwave casting [29]. Fig. 6 shows produced in-situ microwave casts of aluminum, copper, SS 316 and Al 7039 alloy using microwave energy at 2.45 GHz. The time-temperature characteristic of the charge during microwave melting; different stages of the charge heating and conditions of the charge corresponding to the heating stages were reported [30]. The grains found at different locations of the in-situ cast cross section are shown in Figs. 7 a-b. Different phases and their distribution are also presented in Figs. 7 c-d.

Micro indentation geometries and fractographs of the failed in-situ casts during the tensile loading are illustrated in Fig. 8. Typical micro indentation geometries inside the grain (Fig. 8a) and at the grain boundary (Fig. 8b) indicate that presence of intermetallic phases near grain boundaries enhances micro indentation hardness of the in-situ casts. Typical SEM micrographs of the fractured surfaces during the tensile test are shown in Figs. 8 c-d. The study revealed that fracture of cast was in mixed mode; tensile properties in the in-situ microwave cast were reported better as compared to as received alloy [15].

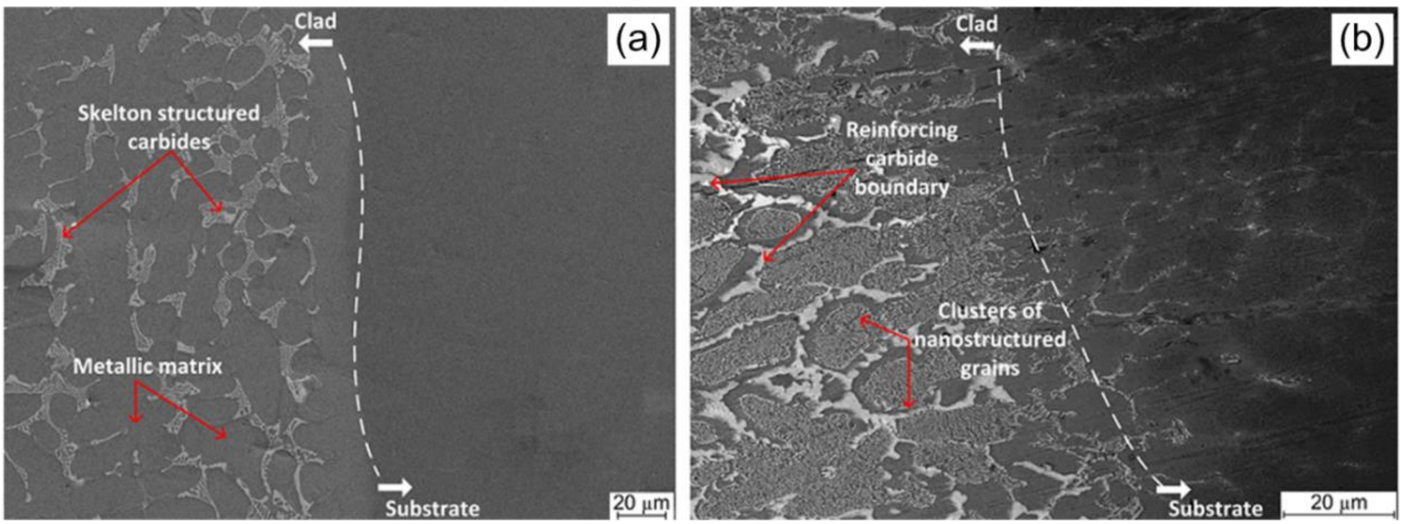

Figure 5: **T**ypical SEM images of (a) micro and (b) nano structured microwave clads [22, 25]

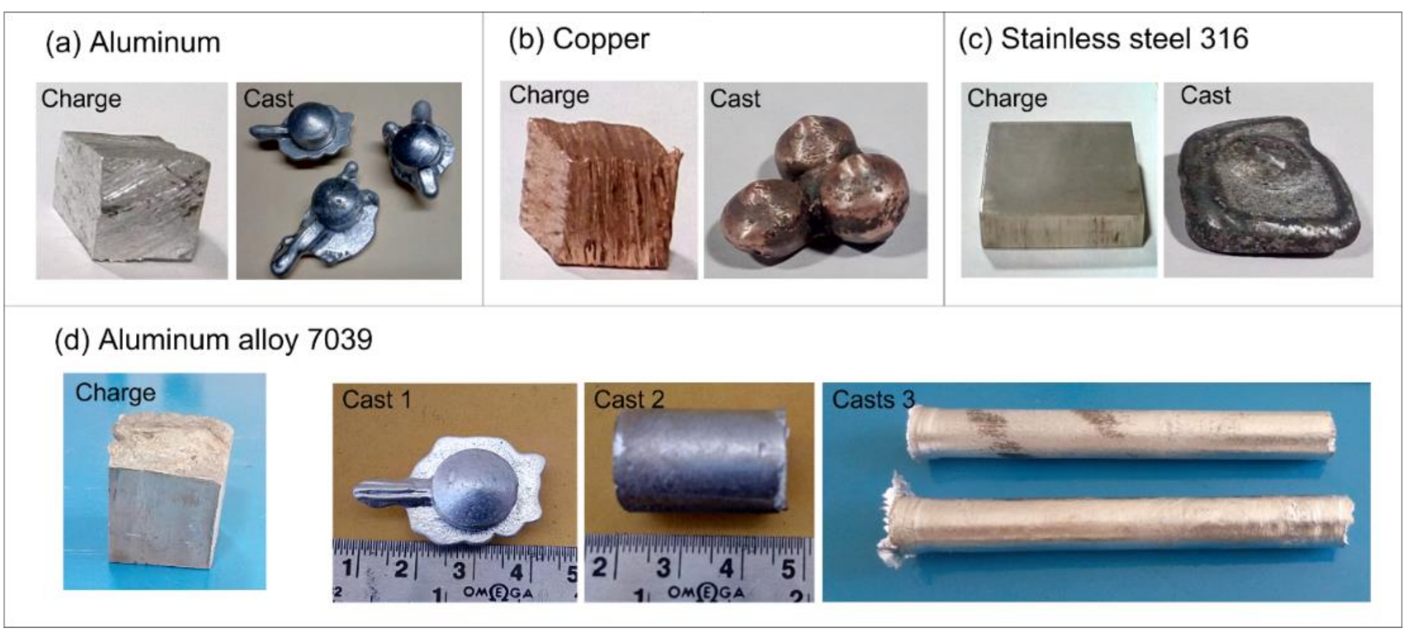

Figure 6: Produced in-situ microwave casts of different metallic materials

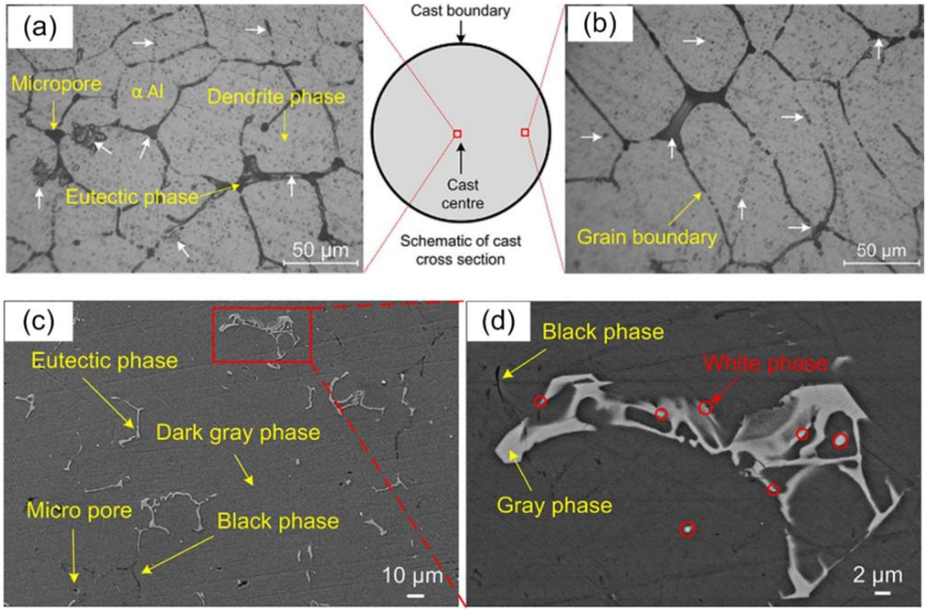

Figure 7: (a-b) optical images of the in-situ cast and (c) SEM image of in-situ cast and (d) enlarged view of the eutectic phase [15]

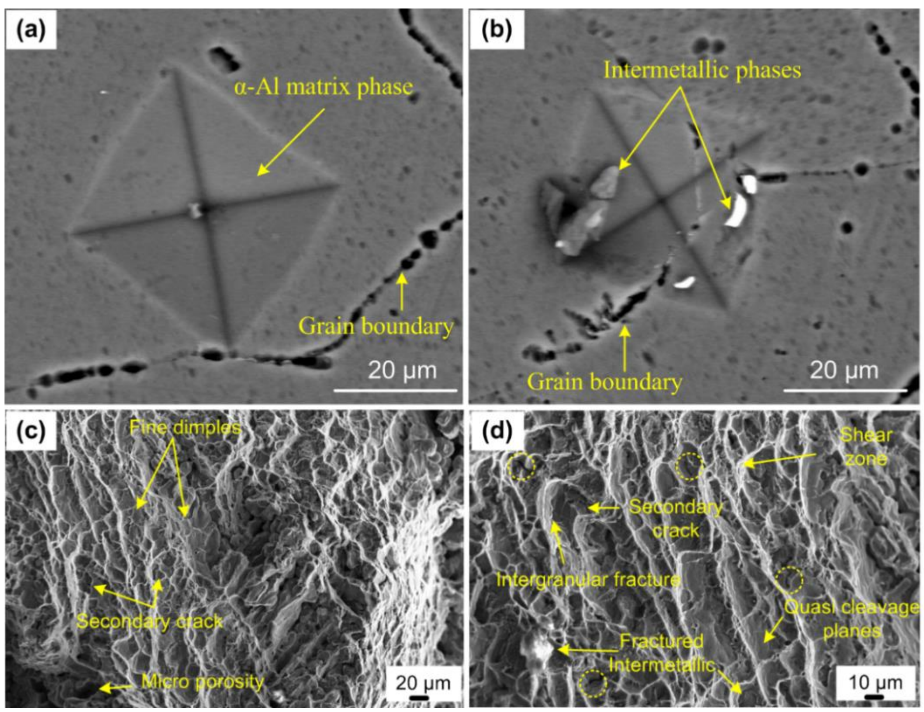

Figure 8: Typical results of in-situ cast of Al 7039 alloy [15] (a) micro indentation geometry inside the grain, (b) micro indentation geometry at the grain boundary and (c-d) fractographs of the failed in-situ casts during tensile test

4.4 Others processes

Microwave energy based other approaches for processing bulk metallic materials which are under development/research phase include microwave drilling and composite casting. Use of microwave energy for composite casting is under investigation. Microwave drilling of some non-metallic materials including glass, was documented and reported by a few research groups globally [31-34]; however, microwave drilling of the metallic materials is an unexplored area. The setups used for microwave drilling of thermal barrier coating (TBC) [31] and soda lime glass [33] and typical results obtained are shown in Figs. 9 a-b. The initial results obtained during the process on stainless steel (SS-304:

0.08% C, 19% Cr, 9% Ni, 2.0% Mn, <1.0% Si, bal. Fe) sheets (Fig. 9 c) using 2.45 GHz microwaves at 700 W revealed feasibility of microwave drilling of the metallic materials. The holes were drilled using a domestic multi-mode microwave applicator with thoriated tungsten tool of 1 mm diameter in atmospheric conditions. The 0.6 mm thick SS-304 sheets were drilled within the exposure range of 70-80 s. However, a significantly large heat affected zone (HAZ) around the hole as seen in Fig.9 c is one of the major concerns. Consequently, control over plasma, repeatability and accuracy are some issues to be addressed in the near future.

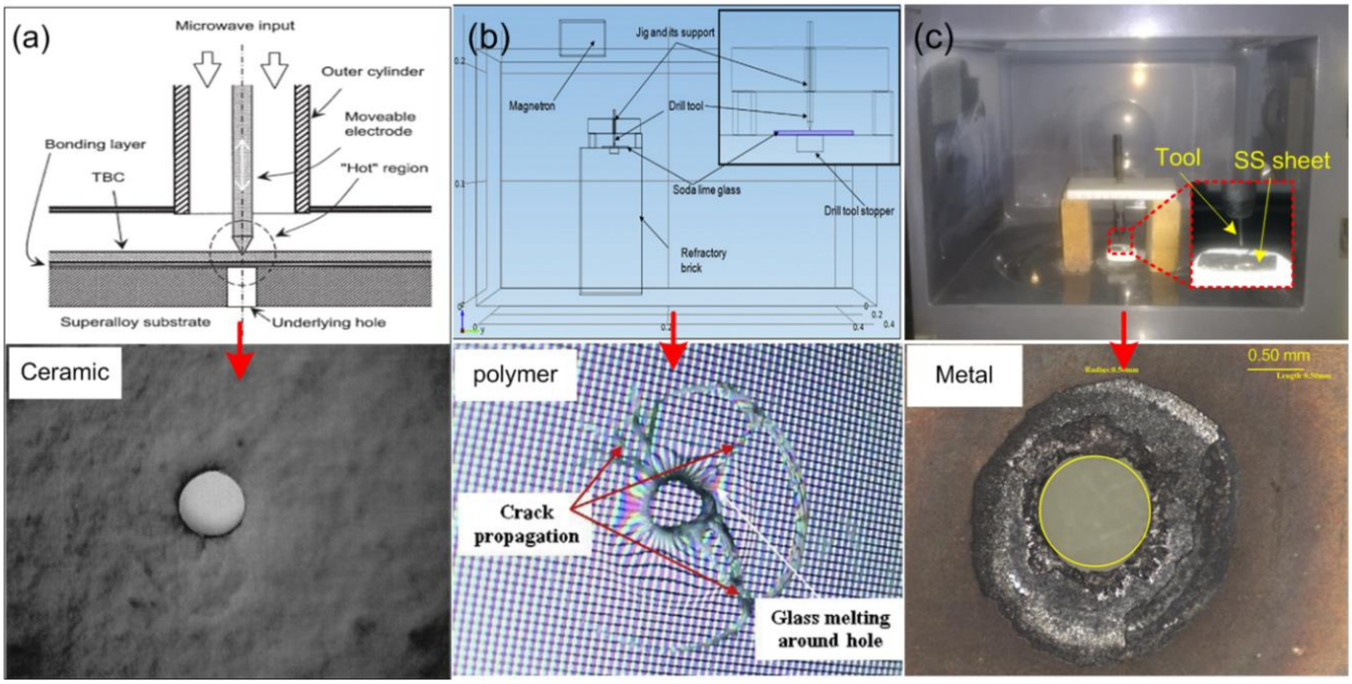

Figure 9: Setup used for microwave drilling and typical holes obtained by (a) Jerby and Thompson on ceramic (TBC) [31], (b) Lautre et al. on soda lime glass [33], and (c) lead author's group on metal (0.6 mm thick SS sheet)

5 Opportunities

In the last few years, significant increase in the literature of microwave processing of bulk metallic materials has been observed. Although most of the microwave based material processing techniques are well documented and gaining fast popularity among the research groups worldwide, these processes are yet far from their industrial applications. This is due to the processing issues such as limitations on the part size, limited control over the process, contamination of the processed part due to tooling materials, constraints in inputs, unexplored process physics, limited mathematical analysis and simulation studies and safety issues in use of microwaves. Thus, the area offers ample research scope to address the processing challenges. Few future research directions in the area are

a) Study of physics involved in microwave-bulk metal interaction
b) Mathematical analysis of the processes
c) Simulation studies to understand the effects of processing conditions
d) Studies on energy efficiency of the processing techniques
e) In-situ measurement of the thermal and electromagnetic properties of the bulk metallic materials during microwave exposure
f) Development of customized applicators to ease the processing with higher flexibility in process control

6 Conclusions

Microwave energy based techniques for processing of the bulk metallic materials have got fast popularity among researchers due to time compression, green energy and better properties in microwave processed parts as compared to conventional processes. Microwave joining and cladding processes are being investigated enthusiastically by the researchers globally; however, the processes are yet to be tuned for industrial applications as alternative of the conventional processes. Research data on microwave casting and drilling are limited and need further investigations to enrich the areas. Study of process physics, development of mathematical models and in-situ monitoring of material properties during microwave exposure will strengthen the domain knowledge which, in turn, will help in achieving better control over the processes.

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For further reading

1. Roy, R.; Agrawal, D.; Cheng, J.; & Gedevanishvili, S.; Full sintering of powdered-metal bodies in a microwave field. *Nature*, 1999, **399**(6737), 668.
2. Leonelli, C.; Veronesi, P.; Denti, L.; Gatto, A.; & Iuliano, L.; Microwave assisted sintering of green metal parts. *Journal of materials processing technology*, 2008, **205**(1), 489-496.
3. Mahmoud, M. M.; Link, G.; & Thumm, M.; The role of the native oxide shell on the microwave sintering of copper metal powder compacts. *Journal of Alloys and Compounds*, 2015, **627**, 231-237.
4. Gupta, M.; & Wong, W. L. E.; Enhancing overall mechanical performance of metallic materials using two-directional microwave assisted rapid sintering. *Scripta Materialia*, 2005, **52**(6), 479-483.
5. Rajkumar, K.; & Aravindan, S.; Microwave sintering of copper–graphite composites. *Journal of Materials Processing Technology*, 2009, **209**(15), 5601-5605.
6. Demirskyi, D.; Agrawal, D.; & Ragulya, A.; Neck growth kinetics during microwave sintering of nickel powder. *Journal of Alloys and Compounds*, 2011, **509**(5), 1790-1795.
7. Mondal, A.; Agrawal, D.; & Upadhyaya, A.; Microwave heating of pure copper powder with varying particle size and porosity. *Journal of Microwave Power and Electromagnetic Energy*, 2008, **43**(1), 5-10.
8. Ro, K.; Dreyer, K.; Gerdes, T.; & Willert-Porada, M.; Microwave sintering of hard metals. International *Journal of Refractory Metals and Hard Materials*, 1998, **16**(4-6), 409-416.
9. Mishra, R. R.; & Sharma, A. K.; Microwave–material interaction phenomena: heating mechanisms, challenges and opportunities in material processing. *Composites Part A: Applied Science and Manufacturing*, 2016, **81**, 78-97.
10. Ripley, E.B. and Oberhaus, J.A. Melting and heat treating metals using microwave heating. *Industrial Heating*, 2005, **72**, 61.
11. Agrawal, D.; Latest global developments in microwave materials processing. *Materials Research Innovations*, 2010, **14**(1), 3-8.
12. Chandrasekaran, S.; Basak, T.; & Ramanathan, S.; Experimental and theoretical investigation on microwave melting of metals. *Journal of Materials Processing Technology*, 2011, **211**(3), 482-487.
13. Moore, A. F.; Schechter, D. E.; & Morrow, M. S.; *U.S. Patent No. 7,011,136*. Washington, DC: U.S. Patent and Trademark Office, 2006.
14. Mishra, R. R.; & Sharma, A. K.; On mechanism of in-situ microwave casting of aluminium alloy 7039 and cast microstructure. *Materials & Design*, 2016, **112**, 97-106.
15. Mishra, R. R.; & Sharma, A. K.; Structure-property correlation in Al–Zn–Mg alloy cast developed through in-situ microwave casting. *Materials Science and Engineering: A*, 2017, **688**, 532-544.
16. Srinath, M. S.; Sharma, A. K.; & Kumar, P.; A new approach to joining of bulk copper using microwave energy. *Materials & Design*, 2011, **32**(5), 2685-2694.
17. Srinath, M. S.; Sharma, A. K.; & Kumar, P.; Investigation on microstructural and mechanical properties of microwave processed dissimilar joints. *Journal of Manufacturing Processes*, 2011, **13**(2), 141-146.
18. Bansal, A.; Sharma, A. K.; Kumar, P.; & Das, S.; Characterization of bulk stainless steel joints developed through microwave hybrid heating. *Materials Characterization*, 2014, **91**, 34-41.
19. Bansal, A.; Sharma, A. K.; Kumar, P.; & Das, S.; Structure–property correlations in microwave joining of Inconel 718. *JOM*, 2015, **67**(9), 2087-2098.
20. Bansal, A.; Sharma, A. K.; Das, S.; & Kumar, P.; On microstructure and strength properties of microwave welded Inconel 718/stainless steel (SS-316L). *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 2016, **230**(5), 939-948.
21. Gamit, D.; Mishra, R. R.; & Sharma, A. K.; Joining of mild steel pipes using microwave hybrid heating at 2.45 GHz and joint characterization. *Journal of Manufacturing Processes*, 2017, **27**, 158-168.

22. Zafar, S.; & Sharma, A. K.; Abrasive and erosive wear behaviour of nanometric WC–12Co microwave clads. *Wear*, 2016, **346**, 29-45.
23. Zafar, S.; & Sharma, A. K.; Structure-property correlations in nanostructured WC–12Co microwave clad. *Applied Surface Science*, 2016, **370**, 92-101.
24. Zafar, S.; & Sharma, A. K.; Development and characterisations of WC–12Co microwave clad. *Materials Characterization*, 2014, **96**, 241-248.
25. Zafar, S.; & Sharma, A. K.; On friction and wear behavior of WC-12Co microwave clad. *Tribology Transactions*, 2015, **58**(4), 584-591.
26. Gupta, D.; & Sharma, A. K.; Development and microstructural characterization of microwave cladding on austenitic stainless steel. *Surface and Coatings Technology*, 2011, **205**(21), 5147-5155.
27. Gupta, D.; & Sharma, A. K.; Microwave cladding: a new approach in surface engineering. *Journal of Manufacturing Processes*, 2014, **16**(2), 176-182.
28. Mishra, R. R.; & Sharma, A. K.; A review of research trends in microwave processing of metal-based materials and opportunities in microwave metal casting. *Critical Reviews in Solid State and Materials Sciences*, 2016, **41**(3), 217-255.
29. Mishra, R. R.; & Sharma, A. K.; Effect of susceptor and mold material on microstructure of in-situ microwave casts of Al-Zn-Mg alloy. *Materials & Design*, 2017, **131**, 428-440.
30. Mishra, R. R.; & Sharma, A. K.; On melting characteristics of bulk Al-7039 alloy during in-situ microwave casting. *Applied Thermal Engineering*, 2017, **111**, 660-675.
31. Jerby, E.; & Thompson, A. M.; Microwave drilling of ceramic thermal-barrier coatings. *Journal of the American Ceramic Society*, 2004, **87**(2), 308-310.
32. Jerby, E.; Dikhtyar, V.; Aktushev, O.; & Grosglick, U.; The microwave drill. *Science*, 2002, **298**(5593), 587-589.
33. Lautre, N. K.; Sharma, A. K.; Kumar, P.; & Das, S.; A photoelasticity approach for characterization of defects in microwave drilling of soda lime glass. *Journal of Materials Processing Technology*, 2015, **225**, 151-161.
34. Lautre, N. K.; Sharma, A. K.; Das, S.; & Kumar, P.; On Crack Control Strategy in Near-Field Microwave Drilling of Soda Lime Glass Using Precursors. *Journal of Thermal Science and Engineering Applications*, 2015, **7**(4), 041001.

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