Processing of MMC through conventional sintering and spark plasma sintering process: A review

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Abstract. Spark plasma sintering (SPS) is one of the advanced methods to produce MMC with the desired quality. The high amount of heat was achieved through direct pulse heating to enhance the diffusion mechanism and it’s involved in the grain growth. Many of the researchers are doing the development of the sintering process for attaining better substance properties with lesser time. SPS was used to fabricate all kinds of materials including ceramics, glass, etc., Direct heat was applied to the graphite die and compact unit. The rate of heat was an essential role in this process to control the densification of powder particles. In the present situation, aluminium MMC plays an essential role in every field such as automobile, aerospace, manufacturing, and electrical sectors. It has superior substance properties such as specific strength, creep, toughness, and corrosion resistance. These properties are enhanced through the addition of reinforcements to the base metal.

1. Introduction
Demand for MMC in proven corrosion resistance environment applications has increased in recent days [1]. MMCs are more resistant to wear and have a much smaller weight, greater strength, and stiffness [2-5]. In SPS, the thermal gradients were controlled and the uniform heating was maintained. It was one of the hybrid heating systems which were suitable for refractory powder particles. The possibility of densifying powders was also controlled through SPS. This is the best method to fabricate ceramics with good properties such as magnetic [6], piezoelectric [7], thermo-electric [8], and optical [9]. The homogeneous material structure, high density, and low defects were attained for the use of ceramics [9-11]. The coarse microstructure was appeared in sintered based components due to longer
heating and soaking methods. The structural properties have been improved through SPS. The uniform AC or DC pulsed current was applied to heat the components \[11\]. The plasma was generated between the contacts of powder particles \[13-14\]. The SPS has unique advantages like as low power consumption, surface cleaned due to electric discharges, and good quality of the components. The applications of Al-MMC have been increased in all sectors like the structural and automotive industry due to greater and mechanical performances and resistance of wear \[15-24\]. The two reinforcements were regularly used in Al MMC such as silicon carbides and aluminium oxides \[25\]. The wear resistance and toughness have been improved through boron carbide reinforcements \[26\]. The better mechanical properties and low thermal expansion were achieved in Al MMC through the reinforcement of silicon carbides and aluminium oxides \[27\]. The surface roughness of the Al MMC was measured during the machining process. The cutting speed and weight percentage of SiC were affecting the surface roughness \[28-29\].

The present investigation was used to provide the idea of processing of MMC through conventional sintering and spark plasma sintering process. The different kinds of literature have been collected related to the conventional sintering and spark plasma sintering process.

2. Materials and role of reinforcements

The quality and structure of the MMC mainly depended on the composition of the alloying elements, the weight percentage of the reinforcements, material processing techniques, and the finishing process. The accumulation of reinforcements was used to strengthening materials through the variation of material properties. The different reinforcements were used to improve the quality of the aluminium MMC such as SiC, B\textsubscript{4}C, TiC, aluminium oxides, fibers, tungsten carbides, and fly ash. The cutting properties that have been evaluated in SiC reinforced Al 6061 and abrasive wear on the tool was investigated \[30\]. The aluminium reinforced with its oxides was prepared through an electromagnetic stir casting route. It was used to enhance the strength of the material and grain size \[31\]. Through the hot pressing methods, titanium and boron tri oxides were reinforced to the Al and its characteristics have been discussed \[32\]. The surface quality characteristics were performed in boron carbide reinforced Al MMC and its quality mainly depended on material removal \[33\]. The zircon glass particles were reinforced with Al through the powder metallurgy route and its compressive strength was discussed \[34\]. The fly ash was used for the production of Al 2024 MMC and a larger accumulation of fly ash was reduced the tensile strength of the material \[35\]. The corrosion resistance was decreased due to the accumulation of fly ash in aluminium composite \[36\]. The strength and nature of the materials were related to the reinforcement of the particles \[37-42\]. It has provided a better material structure during the sintering process.

3. Conventional Sintering Process

The materials were filled inside the die cavity and then it was closed. The punching pressure was applied through a compression testing machine with different loads with respect to the materials. Then it was moved to the sintering process and it was processed at a particular temperature to the nature of the workpiece. The rate of heat was utilized up to 5°C/min. During these periods, the interdiffusion takes place and the powder particles were bonded with adhesion properties. The size of the particle and its weight percentage was decided on the microstructure of the materials \[43\]. The SiC-based Al MMC was produced through a spark plasma sintering process. The matrix properties and their characteristics were examined \[44\]. The blending of powder and compaction pressure was played an important role in material composites. The sintering temperature was used to strengthen the composite and it’s enhancing the hardness of the MMC. The heating and cooling rate were varied in the conventional sintering process. The controlling of temperature was also difficult.

4. Spark plasma sintering method

The SPS process was shown in Fig.1. It consists of a die, punch, vacuum chamber, and electrodes.
The metal powders were placed in die units. The pressure was applied through punches. The sparks have been generated when two electrodes were connected to the DC power supply. The DC pulsed current has produced the heat and it was focused on the metal powders through punches. The sintering temperature, current, and oil pressure were controlled through the proper system. The SPS process and its characteristics were investigated [45]. The plasma was generated between the particles and it was used to improve the interfacial strength of the materials [46]. The densification, plastic deformation, activation, and refining of the powder were the important factors that were used for material processing [47-49]. The SPS input parameters such as temperature, holding time, and heating rate and its effect on the quality of the material were reported [50]. The sintering temperature was the most influential factor in the density and yield strength of the materials [51]. The process factors affected the substance properties and it was concluded that the compaction pressure provided good relation to the responses [52]. The modern technologies used in SPS for the processing of powder materials based on pulsed electricity [53-54].

5. Effect of parameters
The effect of graphene and silicon carbide nanoparticle reinforcement and its mechanical and tribological properties were investigated in spark plasma sintered magnesium matrix composites [55]. The particle size and effects were related to the Densification mechanisms [56]. The particle effect was studied in the microwave sintering process [57-58]. The film oxides on aluminium powders were observed during the electrical sintering process [59]. Carbon nanotubes and their effects on mechanical properties were analyzed [60-63]. The ceramics-based particles were processed under a high temperature-high pressure method [64]. The quality of the composite was depended on the mixing of metal powder particles [65]. The effect of sintering temperature on the microstructure of the materials and its behaviors was studied [66]. The parametric effect on hot pressing was reported in SPS [67]. The porosity effect on spark sintered titanium was studied [68-69]. The sintering temperature has been played an essential role in the material structure [70]. The alloying elements and sintering behaviors were closely related to the surface quality of the composite [71-72].

6. Conclusions
The following summary of conclusions is drawn from the study of the above kinds of literature:

- The metal matrix, particularly aluminium, and its reinforcements were discussed.
- The characteristics of the reinforcements were studied.
- The effect of reinforcement with MMC was investigated.
- The sintering and SPS operation details and features were discussed.
• The comparison of conventional and SPS process and its processing of materials have been studied.
• The different effects of particles on material quality were studied.
• The sintering temperature was the main parameter which affects the microstructure of the material.
• The strength of the material depends on the alloying elements and its SPS parameters.

7. References
[1] Stalin B, Sudha G T, Kailasanathan C and Ravichandran M 2020 Mater. Today Commun. 25 101655 https://doi.org/10.1016/j.mtcomm.2020.101655
[2] Stalin B, Vidhya V S, Ravichandran M, Naresh Kumar A and Sudha G T 2020 Metallofiz. Noveishie Tekhnol. 42(4) 497 https://doi.org/10.15407/mfint.42.04.0497
[3] Dhinakaran V, Stalin B, Swapna Sai M, Vairamuthu J, Marichamy S 2020 Recent developments of graphene composites for energy storage devices Mater. Today:. Proc. https://doi.org/10.1016/j.matpr.2020.08.631
[4] Arravind R, Sankar V, Marichamy S and Stalin B 2020 Abrasive water jet experimentation on zirconium boride and boron carbide reinforced molybdenum metal matrix Mater. Today:. Proc. https://doi.org/10.1016/j.matpr.2020.07.667
[5] Malini T, Sudha R, Anantha Christu Raj P and Stalin B 2020 The role of RTD and liquid sensors in electric arc furnace for melting of aluminium Mater. Today:. Proc. https://doi.org/10.1016/j.matpr.2020.08.371
[6] Aubert A, Loyau V, Mazaleyrat F and LoBue M 2017 Journal of the European Ceramic Society 37 (9) 3101
[7] Li et al. 2006 Journal of the American Ceramic Society 89 (2) 706
[8] Wang et al. 2006 Applied Physics Letters 88 (9) 092104. doi:10.1063/1.2181197
[9] Kim et al. 2007 Scripta Materialia 57 (7) 607. doi:10.1016/j.scriptamat.2007.06.009
[10] Fahrenholtz W G, Wuchina E J, Lee W E and Zhou Y 2014 Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications (New Jersey: John Wiley & Sons, Inc)
[11] Basu B and Balani K 2011 Advanced Structural Ceramics (New Jersey: John Wiley & Sons, Inc)
[12] Shen Z, Johnson M, Zhao Z and Nygren M 2002 J. Am. Ceram. Soc. 85 1921
[13] Inoue K 1965 US Patent No. 3,188, 245.
[14] Yanagisawa O, Hatayama T and Matsugi K 1994 Materia Japan 33 1489
[15] Ralph B, Yuen H C and Lee W B 1997 J. Mater. Proc. Technol. 63 339
[16] Sudha G T, Stalin B and Ravichandran M 2019 Mater. Res. Express 6 096520 https://doi.org/10.1088/2053-1591/ab2cef
[17] Vairamuthu J, Senthil Kumar A, Stalin B and Ravichandran M 2020 Optimization of powder metallurgy parameters of TiC and B,C reinforced aluminium composites by Taguchi method Trans. Can. Soc. Mech. Eng. https://doi.org/10.1139/tcsme-2020-0091
[18] Rajaparthiban J, Saravanavel S, Ravichandran M, Vijayakumar K and Stalin B 2020 Mater. Today:. Proc. 24 1282 https://doi.org/10.1016/j.matpr.2020.04.443
[19] Stalin B, Sudha G T and Ravichandran M 2020 Mater. Today:. Proc. 22 2622 https://doi.org/10.1016/j.matpr.2020.03.393
[20] Alagarsamy S V, Ravichandran M, Raveendran P and Stalin B 2019 J. Balk. Tribol. Assoc. 25(3) 730
[21] Stalin B, Ramesh Kumar P, Ravichandran M, Siva Kumar M and Meignanamoorthy M 2019 Mater. Res. Express 6 106590 https://doi.org/10.1088/2053-1591/ab5d90
[22] Stalin B, Ravichandran M, Vadivel K and Vairamuthu J 2020 Mater. Today:. Proc. 21 237 https://doi.org/10.1016/j.matpr.2019.04.226
[23] Stalin B, Sudha G T and Ravichandran M 2018 Silicon 10 (6) 2663 https://doi.org/10.1007/s12633-018-9803-6
[24] Marichamy S, Stalin B, Ravichandran M and Sudha G T 2020 Mater. Today.: Proc. 24 1400 https://doi.org/10.1016/j.matpr.2020.04.458
[25] Narayana Murty S V S, Nageswara Rao B and Kashyap B P 2003 Composites Science and Technology 63 119
[26] Barbara Previtali, Dante Pocci and Cataldo Taccardo 2008 Composites: Part A 39 1606.
[27] Sujan D, Oo Z, Rahman M E, Maleque M A and Tan C K 2012 Engineering and Applied Sciences 6 288
[28] Palanikumar R and Karthikeyan R 2007 Materials and Design 28 1584.
[29] E K and Inan A 2005 Materials Processing Technology 164-165 862.
[30] Quan Yanning and Zhou Zehua 2000 Materials Processing Technology 100 194.
[31] Kannan S and Kishawy H A 2006 International Journal of Machine Tools & Manufacture 46 2017.
[32] Tjong S C, Wang G S, Geng L and Mai Y W 2004 Composites Science and Technology 64 1971.
[33] Mahesh Babu T S, Aldrin Sugin M S and Muthukrishnan N 2012 Procedia Engineering 38 2617.
[34] Scudino S, Liu G, Prashanth K G, Bartusch B, Surreddi K B, Murty B S and Eckert J 2009 Acta Materialia 57 2029.
[35] Zuoyong Dou, Gaohui Wu, Xiaoli Huang, Dongli Sun and Longtao Jiang 2007 Composites Part A 38 186.
[36] Ramachandra M and Radhakrishna K 2007 Wear 262 1450.
[37] Stalin B, Ramesh Kumar P, Ravichandran M and Saravanan S 2018 Mater. Res. Express 5(10) 106502 https://doi.org/10.1088/2053-1591/aad99c
[38] Marichamy S, Saravanan M, Ravichandran M and Stalin B 2017 Int. J. Mech. Mech. Eng. 21(1) 57
[39] Stalin B, Ravichandran M, Mohanavel V, Praveen Raj L 2020 J. Min. Metall. Sect. B. 56(1) 99 https://doi.org/10.2298/JMMB190315047S
[40] Pritima D, Vairamuthu J, Gopi Krishnan P, Marichamy S, Stalin B and Sheeba Rani S 2020 Response analysis on synthesized aluminium-scandium metal matrix composite using unconventional machining processes Mater. Today.: Proc. https://doi.org/10.1016/j.matpr.2020.07.672
[41] Anix Joel Singh J, Vishnu Vardhan T, Vairamuthu J, Stalin B, Ram Subbiah 2020 Analyses of particle size and abrasive water jet drilling of synthesized chromel metal matrix Mater. Today.: Proc. https://doi.org/10.1016/j.matpr.2020.08.441
[42] Martin Sahayaraj J, Arravind R, Subramanian P, Marichamy S, Stalin B 2020 Artificial neural network based prediction of responses on eglin steel using electrical discharge machining process Mater. Today.: Proc. https://doi.org/10.1016/j.matpr.2020.07.664
[43] Mehdi Rahimian, Nader Parvin and Naser Ehsani 2010 Materials Science and Engineering A 527 1031.
[44] Nouari Saheb, Ismaila Kayode Aliyu, Syed Fida Hassan and Nasser Al-Aqeeli 2014 Materials 7 6748. Doi:10.3390/ma7096748
[45] Munir Z A, Tamburini U A and Ohyanagi M 2006 Journal of Materials Science 41(3) 763.
[46] Hulbert D M, Anders A, Andersson J, Lavernia E J and Mukherjee A K 2009 Scripta Materialia 60(10) 835.
[47] Zhaohui Z, Fuchi W, Lin W, Shukui L and Osamu S 2008 Materials Letters 62(24) 3987.
[48] Zhang Z H, Wang F C, Wang L, Li S K, Shen M W and Osamu S 2008 Materials Characterization 59(3) 329.
[49] Nouari Saheb, Zafar Iqbal, Abdullah Khalil, Abbas Saeed Hakeem, Nasser Al Aqeeli, Tahar Laoui, Amro Al-Qutub and Rene Kirchner 2012 Journal of Nano materials 2012 1 Article ID 983470, Doi:10.1155/2012/983470
[50] Zhang Z H, Wang F C, Wang L and Li S K 2008 Materials Science and Engineering A, 476 (1-2) 201.
[51] Zhang Z H, Wang F C, Lee S K, Liu Y, Cheng J W and Y Liang 2009 Materials Science and
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