Sustainable Development of Light-weight Composites with Recycled Aluminium and Mild Steel Chips Through Conventional Stir Casting

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Abstract:

In the present work, three composites have been developed by reinforcing Mild Steel (MS) chips in the amounts of 1 wt. %, 2 wt. % 3 wt. % respectively to recycled Aluminium chips through manual stir casting process. To further increase the strength, the developed composites were hot rolled at 200^0C to 50% reduction. The microstructure showed that the addition of MS chips lead to grain refinement in the matrix due to the promotion of instantaneous nucleation. Further, it was observed that the composite developed by reinforcing 2 wt. % MS chips exhibited better grain refinement and lowest grain size among the others, which also exhibited highest hardness and compression strength of 83 Hv and 563 MPa respectively which are 26% and 15.3% respectively as compared to the unreinforced alloy. This improvement in the strength can be attributed to the improved grain refinement, uniform distribution of MS powder in the matrix, formation of secondary phase and dispersion strengthening. However, beyond 2 wt. % addition of MS chips, the grain size started to grow, leading to a decline in the hardness and compression strength. Further, all the hot rolled samples exhibited better properties as compared to their counter parts. The trend of variation in properties after hot rolling, however, remained same as the composite with 2 wt% MS chips showing a highest hardness and compression strength of 106 Hv and 722 MPa respectively.

Key words: Aluminium composites; Machining chips; Metal casting; Microstructure; Mechanical Properties; Hot Rolling; Recycling;

1. Introduction

Use of materials has marked the evolution of human race and their civilization [1-3]. With the technology changing rapidly, demand for advanced materials grew to satisfy the latest needs [4]. Starting from the discovery of Copper, development of metals and composites has come a long way exhibiting extra ordinary properties [5]. Early in the metal age, it was observed that pure metals are too soft for any structural applications and the addition of tin to Copper to make Bronze has revolutionized the art of alloying to attain better properties [6-8]. Development of Bronze marked a new age and ended the prolonged Stone Age. However, the arrival of Iron, which is stronger, harder and tougher than Bronze has put an end to the Bronze Age and this competition, is continued till date [9, 10]. This method of strengthening metals with the addition of small amounts of other metals has opened a huge door for the development of new alloys with better properties [11]. Among the others, metals, its alloys and metal based composites have been rigorously developed in the past century [12]. Aluminium is used in various applications in the economy and is very vital to various industries and sectors.

In industries, aluminium is used for machinery, automobiles, structural frames, food processing, power transmission, transportation, etc [13, 14]. In the year 2021, it was been reported that 68 million tons of aluminium has been consumed globally and the consumption is estimated to increase by 50% by 2030 [15]. Therefore, over the years aluminium composites have been developed with an intention of improving their mechanical properties by using various fabrication methods [16] and processes [17] and types of reinforcements like ceramics [18], Rare Earths [19], recycled materials [20], non-metals [21], toxic wastes [22], etc. However, recycling aluminium chips has become a challenge in the current scenario. Therefore, the present work aims to develop light weight composites from scrap and evaluate its mechanical properties and co-relate them with the corresponding microstructures using conventional metal casting and manual stirring.

2. Materials and Methods

For the present study, aluminium chips and Mild Steel (MS) chips obtained after various machining operations as a by-product were collected from the machine shop of the Mechanical Engineering Department, Geethanjali College of Engineering and Technology, Cheeryal, Hyderabad, India. These chips were collected and cataloged progressively over a period of one semester. The collected MS chips were further crushed to smaller size using a hydraulic forging machine and sieved to a size of 50 mesh. On the other hand, aluminium chips were crushed manually to make lumps of 300 grams each. The starting materials, chips of aluminium and MS and the sequence of steps involved in the development of the composites are shown in Fig. 1.

Fig 1. Steps involved in the development of the composites (a) Aluminium and MS scrap chips/powder, (b) Melting of aluminium, (c) Addition of MS powder and stirring, (d) Molten metal, (e) Ice cool water quenching for solidification and (f) Developed composites.

Initially, an Aluminium lump of 300 grams was put in a crucible and heated in an open hearth kerosene fueled furnace. The crucible was covered with an air tight lid to avoid any unwanted micro inclusions caused by hot flue gases.

A thermocouple was attached to the crucible to monitor the temperature. At 800^0C, the lump started to melt and reached complete liquefaction at around 850^0C. The crucible was removed from the furnace after achieving molten state and the MS powder was introduced to the molten aluminium in three stages. The MS powder was divided into three equal parts and after introducing each part into the crucible, the molten mixture was manually stirred for 5 minutes using a thin Stainless Steel rod until the mixture starts to solidify and put back into the furnace. Finally, after adding all the amount of reinforcement and stirred, the crucible was kept in a bucket of ice cold water and the molten metal was allowed to rapidly solidify. In this manner, there composites reinforced with varying amounts of MS powder were developed. Also, an unreinforced pure aluminium sample was also cast as a benchmark to study and evaluate the effects of MS powder addition.

The developed samples were cut into convenient pieces for further characterization and testing. Also, suitable samples were cut for hot rolling. Samples of 30x30x20 mm were cut and hot rolled at 200^0C up to 50% reduction in 10 passes with a 5% reduction and water quenching after each pass. The rolled samples were also characterized and tested; and their properties were compared with that of the unrolled samples.

3. Results and Discussion

3.1 Density

The developed samples were cut precisely into 1.5 X 1.5 X 1 cm blocks for density testing. The theoretical density of the composites was calculated through the Rule of mixtures and the experimental density was measured using Archimedes principle [23]. The relative density of the developed composites was calculated using Equation (1).

$$\text{Relative Density (RD)} = \frac{\text{Experimental density}}{\text{Theoretical density}} \text{.................. (1)}$$

The intended composition and relative density of the developed composites is shown in Table 1 below. From Table 1, it can be noticed that as the amount of reinforcement increases, the relative density tend to decrease. It is obvious that the theoretical density of the composite increases with an increase in the amount of MS powder as its density is higher than that of aluminium.

Table 1. Intended compositions and relative densities of the developed composites.

S. No.	Aluminium wt%	MS powder wt%	Relative Density %
1	100	0	98.87
2	99	1	97.42
3	98	2	97.23
4	97	3	97.19

The experimental density constantly decreased with an increase in the reinforcement, resulting in the decrease of RD. This phenomenon is expected because of manual stirring during the addition of reinforcement which would have introduced gas bubbles [24].

Also, introduction of the reinforcement and stirring in three stages, displacing the crucible in and out of the furnace for adding reinforcement, quenching the molten mixture in ice cold water, which did not provide enough time for the entrapped gas bubbles to escape to the surface, could be the main reasons for the formation of pores in the composites [25]. However, the decrease in the RD of the composite samples is very less and well above 97 %.

3.2 Microstructure Characterization

One piece from each developed composite was cut and prepared for microstructure observations. An Optical Microscope (Make: Upright Microscope) was used for the microstructure observations. The samples were prepared in line with the ASTM standards. The samples were polished on 400, 600, 800, 1200, 1500 and 2000 silicon carbide emery papers respectively. Next, the samples were cloth polished using diamond paste to get a mirror polished surface. The polished samples were then etched with modified Keller's reagent for 35-45 seconds and thoroughly washed, air dried and made ready for microstructure observations [26]. The microstructures of the developed composites are shown in Fig. 2 below. From Fig 2, the change in microstructures with an increase in MS powder addition can be clearly observed. It is also evident from the microstructures that the grain refinement increases from Fig 2 (a) to (c) and after that, abruptly, the grains tend to grow. Moreover, a needle like secondary phase can be seen in Fig 2 (b) to (d) which get finer and increase in number up to Fig 2 (c) and become coarser in (d).

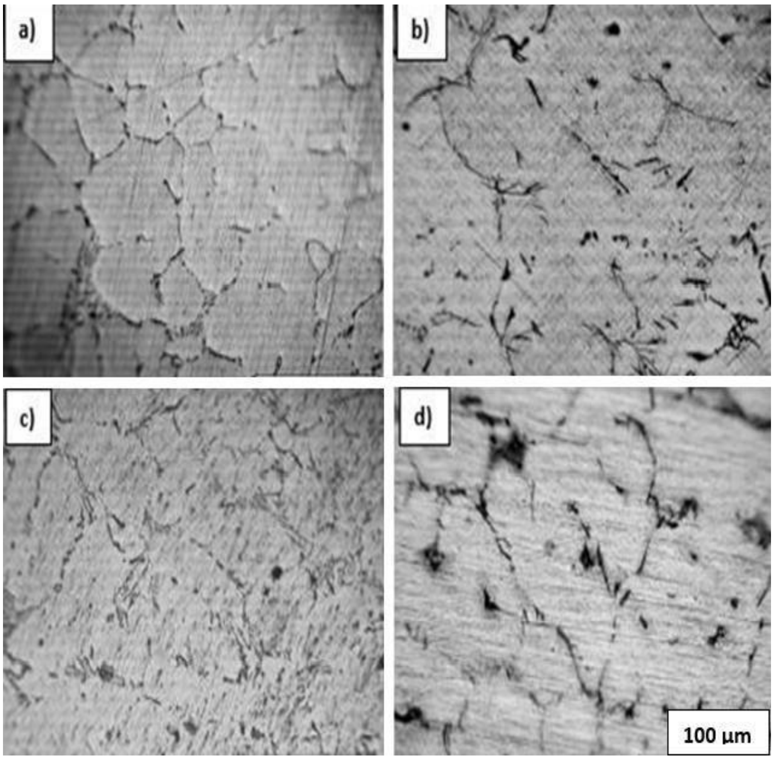

Fig 2. Optical microstructures of the developed composites reinforced with MS powder (a) 0 wt.%, (b) 1 wt.%, (c) 2 wt. % & (d) 3 wt. %.

The change in mechanical properties such as hardness and compression strength can be attributed to both grain refinement and development of fine secondary phase [27]. The mechanical properties of the composites improve as the grain size decreases and finer secondary phase increases up to 2 wt% addition of MS powder.

However, the properties tend to decrease as the grain size increases and the secondary phase become coarser when the amount of MS powder addition increases beyond 2 wt%. This can be due to the fact that finer MS powder particles get agglomerated and its distribution gets effected as its amount increases [28]. The microstructures of the developed samples hot rolled at 200^0C up to 50% reduction are shown in Fig. 3. The rolling direction is shown by solid red arrows in Fig 3. As discussed earlier, grain refinement was evident in the composites due to the addition fine MS powder. During hot rolling, the grains were elongated in the direction of rolling accommodating themselves in a manner that eliminates any pores that were present during the initial fabrication. It can be observed from Fig 3 that the composites were densified [29]. Also, the secondary phase was uniformly redistributed due to the raise in temperature and pressure applied during rolling.

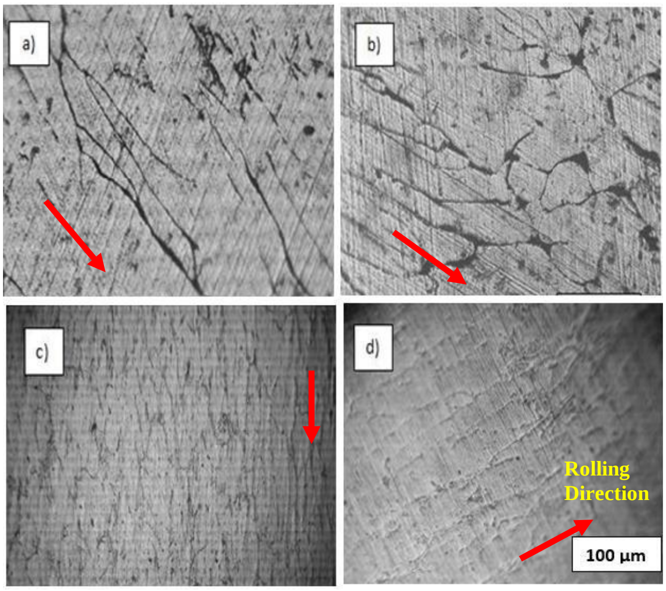

Fig 3. Optical microstructures of cross-sections of samples hot rolled at 200^0C up to 50% reduction reinforced with MS powder (a) 0 wt.%, (b) 1 wt.%, (c) 2 wt. % & (d) 3 wt. %.

Moreover, due to severe plastic deformation, it can be observed from Fig 3 (c) that the elongated grains were further broken along their length, decreasing the grain size and thus, increasing the number of grains and grain boundaries [30]. Initially, the secondary phase was concentrated between the elongated grains. However, with 2 wt% MS powder reinforcement, it can be observed that the secondary phase is broken into smaller amounts and distributed uniformly.

3.3 Mechanical Properties

The developed composites were cut into appropriate shapes and sizes according to ASTM standards for mechanical testing. Micro hardness testing was conducted on the prepared samples using a computerized Vickers hardness testing machine, while the compression test was done on a Universal testing machine according to ASTM E8 standards. Ten readings were taken on each sample at points spread across the surface and the average is reported along with the maximum and minimum values.

Similarly, three samples from each composite were compressed and the average value is reported. The micro hardness of the composites before and after hot rolling is showed in Fig. 4.

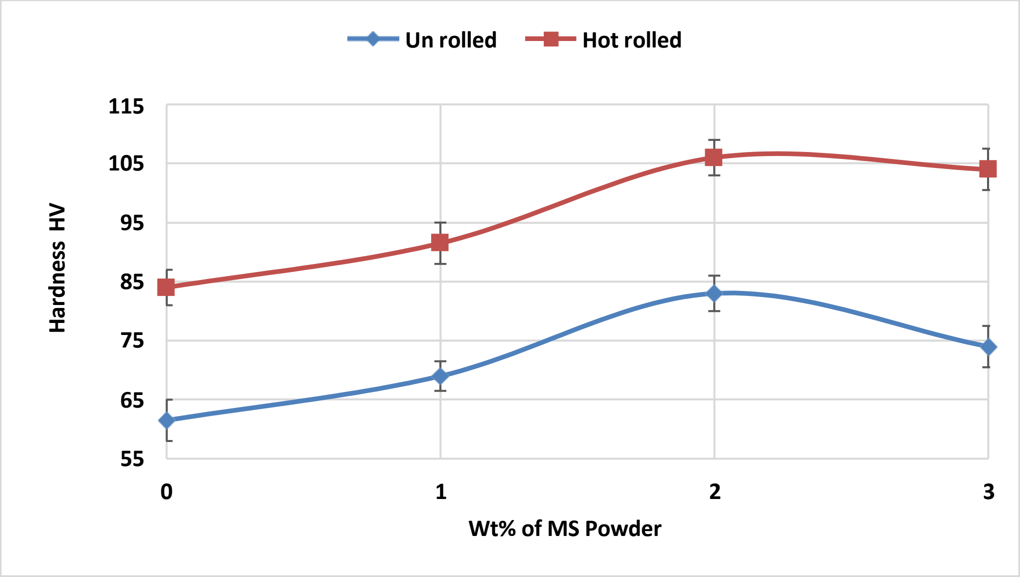

Fig 4. Micro hardness variation of the developed composites with varying amounts of MS powder before and after hot rolling.

From Fig 4, the trend followed by the micro hardness with an increase in the amount of MS powder can be clearly seen. With an increase in the amount of MS powder addition, hardness tends to gradually increase up to 2 wt%. However, beyond 2 wt% addition of MS powder, hardness tends to drop. On the other hand, hot rolled samples also followed a similar trend as that of unrolled samples. However, there is an average increase of around 20 Hv between the both. The gradual increase in the hardness can be attributed to the occurrence of grain refinement, Al-Fe secondary phase formation and uniform distribution in the matrix with the addition of MS powder [31]. Similarly, due to hot rolling, the grains got elongated and the secondary phase got redistributed within the matrix at the grain boundaries. Moreover, with further increase in the amount of MS powder, fracture of elongated grains resulting in an increase in the number of grains and grain boundaries within the matrix as seen from Fig 3. Also, severe plastic deformation induced by rolling plays a major role in the improvement of the hardness as it promotes the number of dislocations within the matrix. The decrease in the hardness beyond 2 wt% addition of MS powder can be attributed to the agglomeration of particles and secondary phase in the matrix. Fig 5 shows the variation of compression strength with an increase in the addition of MS powder. The variation in compression strength also follows a similar trend as that of the hardness as seen from Fig 4. This trend of variation can be explained on similar lines as that of hardness. The increase in compression strength, both before and after hot rolling can be attributed majorly to the grain refinement, increase in the number of dislocations due to rolling, further grain size reduction due to rolling, size reduction and uniform distribution of Al-Fe secondary phase [32].

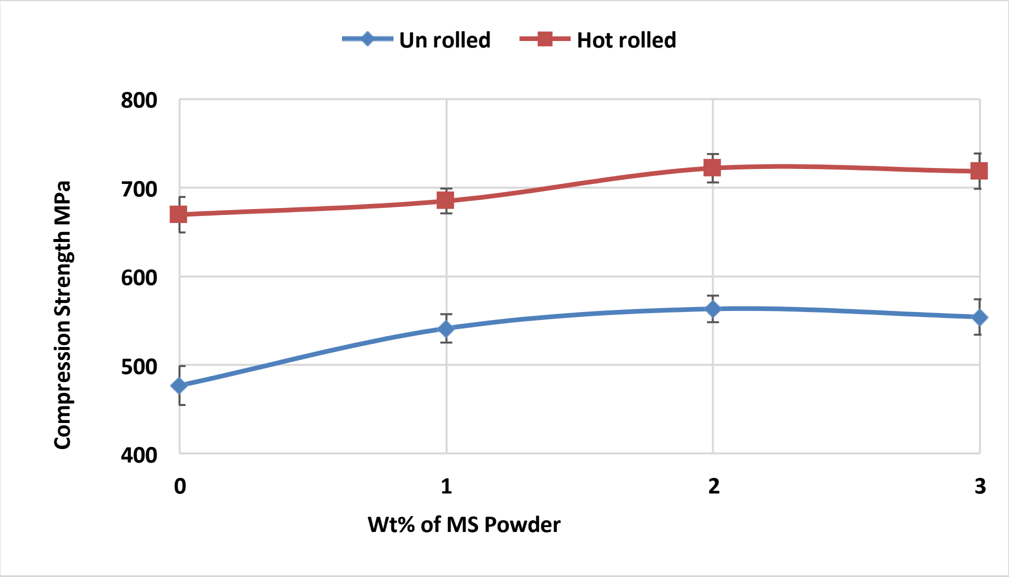

Fig 5. Compression strength variation of the developed composites with varying amounts of MS powder before and after hot rolling.

4. Conclusions:

- In the present study three composites reinforced with varying weight percentages of MS scrap were successfully developed. The micro structure revealed high intensity of grain reinforcement up to 2 wt% of MS powder, beyond which the refinement is not significant.
- The mechanical properties of the developed composites were improved as compared to the unreinforced sample. The sample reinforced with 2 wt% of MS powder exhibited highest hardness and compression strength of 83 Hv and 563 MPa which are 26% and 15.3% respectively as compared to the unreinforced alloy.
- Hot rolling further improved the mechanical properties of the composites and followed a similar trend as that of unrolled samples. The microstructures showed elongated grains, grain fracture, decreased size and uniform distribution of secondary phase within the matrix.
- The sample reinforced with 2 wt% of MS powder exhibited highest hardness and compression strength of 106 Hv which is 21% and 42% as compared to the sample without rolling and unrolled and unreinforced samples respectively. Similarly, the sample reinforced with 2 wt% of MS powder exhibited highest compression strength of 722 MPa which is 22% and 34% as compared to the sample without rolling and unrolled and unreinforced samples respectively.

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References

1. Vojtich D. Challenges for research and development of new aluminium alloys. Metalurgija, 2010, 49: 181–185. https://doi.org/10.1016/j.ymgme.2010.11.164.
2. Toozandehjani M, Kamarudin N, Dashtizadeh Z, Lim E Y, Ashen G, Chandima G. Conventional and advanced composites in aerospace industry, Technologies revisited. American Journal of Aerospace Engineering, 2019, 5: 9–15. https://doi.org/10.11648/j.ajae. 20180501.12.

3. Mekonnen A.F, Mahmut A.S. Materials used in automotive manufacture and material selection using Ashby charts. International Journal of Materials Engineering, 2018, 8(3): 40–54. doi: 10.5923/j.ijme.20180803.02.
4. Tisza M, Czinege I. Comparative study of the application of steels and aluminium in lightweight production of automotive parts. Int J Light Mater Manuf, 2018, 1: 229–238. https://doi.org/10.1016/j.ijlmm.2018.09.001.
5. Davis J.R. Alloying: Understanding the basics. ASM International, 2001, 351–416. https://doi.org/10.1361/ autb2001p351.
6. Rathod N.R, Manghani J.V. Effect of modifier and grain refiner on cast Al-7Si aluminum alloy: A review. Int J Emerg Trends Eng Dev, 2012, 5: 574–582.
7. Campbell J. Sixty years of casting research. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 2015, 46: 4848–4853. https://doi.org/10.1007/s11661-015-2955-8.
8. Oloyede O. Feasibility of replacing structural steel with aluminum alloys in the commercial shipbuilding industries in Nigeria. International Journal of Science and Technological Research, 2012, 9: 188–204.
9. Moona G, Walia R.S, Rastogi V, Sharma R, Aluminium metal matrix composites: a retrospective investigation. Indian J. Pure Appl. Phys, 2018, 56: 164–175.
10. Vidyasagar C.S, Karunakar D.B. Effect of spark plasma sintering and reinforcements on the formation of ultra-fine and nanograins in AA2024-TiB2-Y hybrid composites. Prog. Nat. Sci. Mater. Int, 2021. https://doi.org/10.1016/j.pnsc.2021.07.001.
11. Meena K.L, Vidyasagar C.S & Karunakar D.B. Mechanical and Tribological Properties of Alumina Toughened Zirconia Composites through Conventional Sintering and Microwave Sintering. Trans Indian Inst Met, 2020, 73: 1909–1923. https://doi.org/10.1007/s12666-020-02001-y.
12. Dursun T, Soutis C. Recent developments in advanced aircraft aluminium alloys. Mater. Des, 2014, 56: 862–871. https://doi.org/10.1016/j.matdes.2013.12.002.
13. Jawalkar C.S, Kant S. A review on use of aluminium alloys in aircraft components, I-Manager's. J. Mater. Sci, 2018, 3: 33–38. https://doi.org/10.26634/jms.3.3.3673.
14. Vidyasagar C.S, Karunakar D.B. Effects of nano yttrium and spark plasma sintering on the mechanical properties of AA2024 matrix composites. Met. Mater. Int, 2020. https://doi.org/10.1007/s12540-020- 00727-4.
15. Pulkit G, Anbesh J, Devendra K, Kishor K.S, Chaudherym H, Pallav G. Advance research progresses in aluminium matrix composites: manufacturing & applications. Journal of Materials Research and Technology, 2019, 8(5): 4924–4939. https://doi.org/10.1016/ j.jmrt.2019.06.028.
16. Zhang Peng-xiang, Hong Yan, Wei Liu, ZOU Xiu-liang, TANG Bin-bing. Effect of T6 heat treatment on microstructure and hardness of nanosized Al2O3 reinforced 7075 aluminum matrix composites. Metals, 2019, 9(44): 1–12. doi:10.3390/met9010044.
17. Vidyasagar C.S, Karunakar D.B. Effects of yttrium addition and aging on mechanical properties of AA2024 fabricated through multi-step stir casting. Trans. Nonferrous Met. Soc. China (English Ed), 2020, 30: 288–302. https://doi.org/10.1016/S1003-6326(20)65213-X.
18. Ayar V.S, Sutaria M.P. Development and characterization of in situ AlSi5Cu3/TiB2 composites. Int. J. Met, 2020, 14: 59–68. https://doi.org/10.1007/s40962-019-00328-x.
19. Vidyasagar C.S, Karunakar D.B. Characterization of mechanical properties and microstructures of spark plasma sintered and cryo-rolled AA2024-Y composites. Trans. Nonferrous Met. Soc. China (English Ed), 2020, 30: 1439–1451. https://doi.org/10.1016/S1003-6326(20)65309-2.

20. Bulei C, Kiss I, Alexa V. Development of metal matrix composites using recycled secondary raw materials from aluminium wastes. Materials Today: Proceedings, 2021, 45: 4143–4149. doi:10.1016/j.matpr.2020.11.926.
21. Rashad M, Pan F, Liu Y, Chen X, Lin H, Pan R, Asif M, She J. High temperature formability of graphene nanoplatelets-AZ31 composites fabricated by stir-casting method. J. Magnes. Alloy, 2016, 4: 270–277. https://doi.org/10.1016/j.jma.2016.11.003.
22. Sudipt Kumar J.A.T, Metal matrix composite production and characterisation of aluminium-fly ash composite using stir casting method production and characterisation of aluminium-fly ash composite using stir casting method. Mater. Eng, 2008, 1–57.
23. Vidyasagar C.S, Karunakar D.B. Improvement of mechanical properties of 2024 AA by reinforcing yttrium and processing through spark plasma sintering. Arab. J. Sci. Eng, 2019, 44: 7859–7873. https://doi.org/10.1007/s13369-019-03924-5.
24. Khalkho J.S, Vidyasagar C.S, Karunakar D.B. Mechanical Properties of AA2014 Matrix Composites Reinforced with TiO_2 Particles Through Multi-step Stir Casting. In: Saran, V.H, Misra, R.K. (eds) Advances in Systems Engineering. Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-15-8025-325.
25. Alagarsamy S.V, Ravichandran M, Synthesis, microstructure and properties of TiO2 reinforced AA7075matrix composites via stir casting route. Mater. Res. Express, 2019. https://doi.org/10.1088/2053- 1591/ab1d3b.
26. Khalkho J.S, Chevuri S.V, Dagarapu B.K. Evaluation of Microstructure and Mechanical Properties of TiO_2 Reinforced Aluminium Composites Developed Through Multi-Step Stir Casting. Inter Metalcast, 2022. https://doi.org/10.1007/s40962-022-00760-6.
27. Prapasajchavet K, Harada Y, Kumai S. Microstructure analysis of Al-5.5 at%Mg alloy semi-solid slurry by weck's reagent. Int. J. Met, 2017, 11: 123–130. https://doi.org/10.1007/s40962-016-0084-9.
28. Aybarc U, Ertugrul O, Seydibeyoglu M.O. Effect of Al2O3 particle size on mechanical properties of ultrasonic-assisted stir-casted Al A356 matrix composites. Int.J.Met, 2021, 15: 638–64. https://doi.org/10.1007/s40962-020-00490-7.
29. Jiang J, Liu Y, Xiao G, Wang Y, Ju Y. Effect of pass reduction on microstructure, mechanical properties and texture of hot-rolled 7075 alloy. Mater. Charact, 2019, 147: 324-339. https://doi.org/10.1016/j.matchar.2018.11.015.
30. Khalkho J.S, Vidyasagar C.S, & Karunakar D.B. Evaluation of Microstructure and Mechanical Properties of Al-TaC Composites Developed by Muti-Step Stir Casting Process. Proceedings of the ASME 2020 15th International Manufacturing Science and Engineering Conference. Volume 1: Additive Manufacturing; Advanced Materials Manufacturing; Biomanufacturing; Life Cycle Engineering; Manufacturing Equipment and Automation. ASME. https://doi.org/10.1115/MSEC2020-8291.
31. Meena K.L, Vidyasagar C.S, Karunakar D.B. Mechanical and Tribological Properties of MgO/Multiwalled Carbon Nanotube-Reinforced Zirconia-Toughened Alumina Composites Developed through Spark Plasma Sintering and Microwave Sintering. J. of Materi Eng and Perform, 2022, 31:682-696. https://doi.org/10.1007/s11665-021-06170-9.
32. Satish D.R, Feyissa F, Kumar D.R. Cryorolling and warm forming of AA6061 aluminum alloy sheets. Mater Manuf Process, 2017, 32: 1345–1352. https://doi.org/ 10.1080/10426914.2017.1317352.