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Combined effect of melt thermal treatment and Sr modifier on microstructure and mechanical properties of hypereutectic Al-14Si alloy

SUNIL MANANI[1*], SANDEEP KUMAR[1], PATEL NIKUNJ[1], AJAYA KUMAR PRADHAN[2]

[1] Ph.D. Scholar, Department of Metallurgical and Materials Engineering, MNIT Jaipur, Jaipur 302017, India;
[2] Assistant Professor, Department of Metallurgical and Materials Engineering, MNIT Jaipur, Jaipur 302017, India
* Corresponding author mail id: 2017rmt9064@mnit.ac.in

Abstract

This research aimed to investigate the combined effect of melt thermal treatment and Sr modifier on microstructure and mechanical properties of hypereutectic Al-14Si alloy. Various characterization techniques and testings such as optical microscopy, scanning electron microscopy, tensile test and hardness test were carried out to evaluate the samples. The results showed that the melt thermal treated alloys have a more refined primary Si phase and modified eutectic Si structure than that of the conventional cast alloys. This led to a considerable improvement in tensile strength, hardness and ductility in the melt thermal treated alloys. The mean size of primary Si and eutectic Si was lesser in the case of the sample that had undergone both melt thermal treatment and Sr-modification than the only Sr-modified alloy. These lead to a significant improvement in mechanical properties of the alloy treated by both melt thermal treatment and Sr-modifier than only Sr-modified alloy.

Keywords: Melt thermal treatment; Primary Si; Eutectic Si; Al-14Si alloy; Sr-Modifier.

1. Introduction

The Al-Si alloys are used to produce various automobile and structural application components because of the lighting of structure compared to ferrous alloys[1-3]. The components such as piston, engine block, cylinder liners of lightweight automobile engines should have a high strength/weight ratio, high fatigue strength, low wear resistance and low thermal expansion coefficient. These requirements can be fulfilled by hypereutectic Al-Si alloys (Si > 13 wt.%) because of hard primary Si and ductile α-Al in its microstructure. However, the presence of large blocky primary Si and needle like eutectic Si causes brittleness in components[4-5].
Various studies have been conducted to refine the primary Si and to modify the eutectic Si morphology, e.g., by the addition of Phosphors (P)[6-7], rare earth elements[8-9] and strontium (Sr)[10-12] as modifiers, by semi solid processing[13], by electromagnetic stirring[14] and by melt thermal rate treatment[15-18]. The addition of P and Sr in hypereutectic Al-Si alloy cause refinement of primary Si and morphological transformation of eutectic Si, respectively[19-20]. Interaction between P and Sr makes it impossible to acquire refinement and modification simultaneously. Electromagnetic stirring technology is an effective, however very costly than the conventional casting process.
Superheating combined with faster cooling, known as melt thermal treatment is a modified casting process that can acquire refinement and modification simultaneously in hypereutectic Al-Si alloy. In this treatment, a portion of the melt is superheated by ~300 ^{o}C cooled to pouring temperature by a low temperature melt followed by pouring. The final cast microstructure depends on the atomic cluster size and distribution of cluster in melt. In conventional casting, melt have large sized non uniform atomic clusters. These lead to large sized phases in final cast structure. In the MTT process, superheating of melt leads to decrease in cluster size and improved cluster distribution. When such a liquid melt structure crystallizes, the final cast structure will have a more refined and uniformly distributed phase. The fast cooling is necessary to freeze superheated melt structure to pouring temperature.
To the best knowledge of the authors, MTT has been studied on Al-20Si alloy[8, 17], Al-18Si alloy[21-22], Al-15Si alloy[10,23], Al-13Si alloy[24] and hypoeutectic alloys[25-26] and no study is conducted on the combined effect on MTT and Sr modifier on Al-14Si alloy. These previous studies have shown that individual MTT processes can reduce the size of primary Si, which leads to improvement in mechanical properties, especially ductility. However, alloys must need further strengthening to fulfil the future requirement of developing industries. Hence, this research aims to study the combined effect of melt thermal treatment and Sr modifier of Al-14Si alloys.

2. Experiment Procedure

In conventional casting process, Al-14Si alloys were prepared by melting commercially pure Al and Al-15Si master alloy in desired proportion at 720 °C in an electrical resistance muffle furnace. The prepared alloy was degasified by adding C2Cl6 tablets into the melt. The modification was carried out by the addition of Al-5Sr master alloy (Sr~ 250 ppm) in selected samples. Finally, with or without modified melt was poured into preheated (250 °C) graphite mould of dimensions 24 mm diameter and 120 mm height for casting.

In melt thermal treatment, prepared Al-14Si melt with or without modifier was divided into two parts. In one part (superheated melt), the melt temperature was raised to 920 °C followed by holding for 15 Min. The other half (low temperature melt) temperature was decreased to 620 °C followed by holding for 15. Then the superheated melt was poured into the low temperature melt followed by manual stirring using a graphite rod and pouring into a preheated (250 °C) graphite mould.

Chemical compositions of commercial pure Al, Al-15Si master alloy and Al-5Sr as investigated by optical emission spectrometer (OES) (Spectrolab) are given in table 1. The sample codes and descriptions of various alloys' casting conditions are given in the table. 2. The prepared alloys were then gone through sectioning, wet grinding (SiC emery paper) and polishing by Al2O3 suspension on a velvet cloth. For microstructure examination, the polished samples were etched using regent (99% distilled water, 1% HF). The microstructure of the alloys was captured with the help of an optical microscope (Zeiss Axio vert. A1) and the size of primary Si and eutectic Si analyzed using ImageJ software. Investigation of change in morphology of eutectic Si with different treatments was carried out using field emission scanning electron microscope (FE-SEM, Nova Nano SEM 450).

The tensile test was carried out at a strain rate of 1 mm/min on a tensile testing machine (Model: H25KL, Tinius Olsen) The two different samples have dimensions (as per ASTM E08 standard) prepared under similar conditions to ensure reproducibility of the results. Fracture analysis of tensile test specimens were carried out using the scanning electron microscope. A Brinell hardness testing machine measured hardness with 500 kgf load and 15 s dwell time. The reported results are the mean of 5 different reading each taken on two different specimens prepared under similar conditions.

Table 1: Chemical composition analysis.

Element	**Si**	**Mg**	**Fe**	**Ti**	**Cu**	**Mn**	**Zn**	**V**	Sr	**Al**
Al	0.221	0.15	0.24	0.04	0.04	0.02	0.02	0.002	-	Bal.
Al-15Si	14.82	0.011	0.15	0.005	0.002	0.003	0.01	0.012	-	Bal.
Al-5Sr	0.100	0.01	0.24	0.006	0.001	0.004	0.001	0.012	4.82	Bal.

Table 2: Sample code of prepared Al-14Si alloys at different casting conditions.

Sample code	**Description of casting condition**
Alloy A	Al-14Si casting via conventional method
Alloy B	Al-14Si casting via melt thermal treatment method
Alloy C	Al-14Si + grain modifier casting via conventional method
Alloy D	Al-14Si + grain modifier casting via melt thermal treatment method

3. Results and Discussion

3.1 Microstructure analysis

Fig. 1 presents microstructure of conventional cast and MTT processed along with or without the addition of modifier Al-14Si alloys. From fig. 1 (a, b), in the case of conventional cast and MTT processed without modifier alloy (A and B), the microstructure has polyhedral or blocky type primary Si and needle shaped eutectic Si. The MTT process decreases the size of primary Si particles from 30.11 μm to 20.47 μm and the distribution of particles is also observed to improve compared with that of alloy A. Moreover, edges of primary Si have converted into rounded from sharp edged surfaces in alloy A. In the case of alloy B, eutectic Si particles have been modified to a certain extent, but morphology remains needle shaped. The mean length of eutectic Si particles has reduced by 14.2 % compared with that of alloy A. From fig. 1(c, d), in the case of both conventional cast with Sr-modifier (C) and MTT processed with Sr-modifier alloy (D), the mean size of primary Si particles reduced compared to that of respective unmodified alloys. The mean size of primary Si particles of the alloy C reduced to 25.7 from 30.11 in the alloy A. Although, quantity of primary Si significantly decreased in the modified alloy. This is because Sr, which only modifies the eutectic Si in Al-Si alloys.

In the case of alloy D, the quantity and size of primary Si particles significantly decreased along with the modification of eutectic Si. The mean size of primary Si particles in alloy D reduced by 49.34 %, 20.23 % and 40.67% compared to that in alloy A, alloy B and alloy C, respectively.

Fig 2 shows SEM microstructure of conventional cast with Sr-modifier (alloy C) and MTT processed with Sr-modifier alloy (alloy D). The results indicated that eutectic Si has been modified into short rod-like or granular like from needle structure (unmodified alloys). However, the modification effect of alloys D on eutectic Si particles is better than in alloy C. The mean length and diameter of eutectic Si particles in alloy D reduced by 15.2 % and 14.7% compared to that of alloy C, respectively.

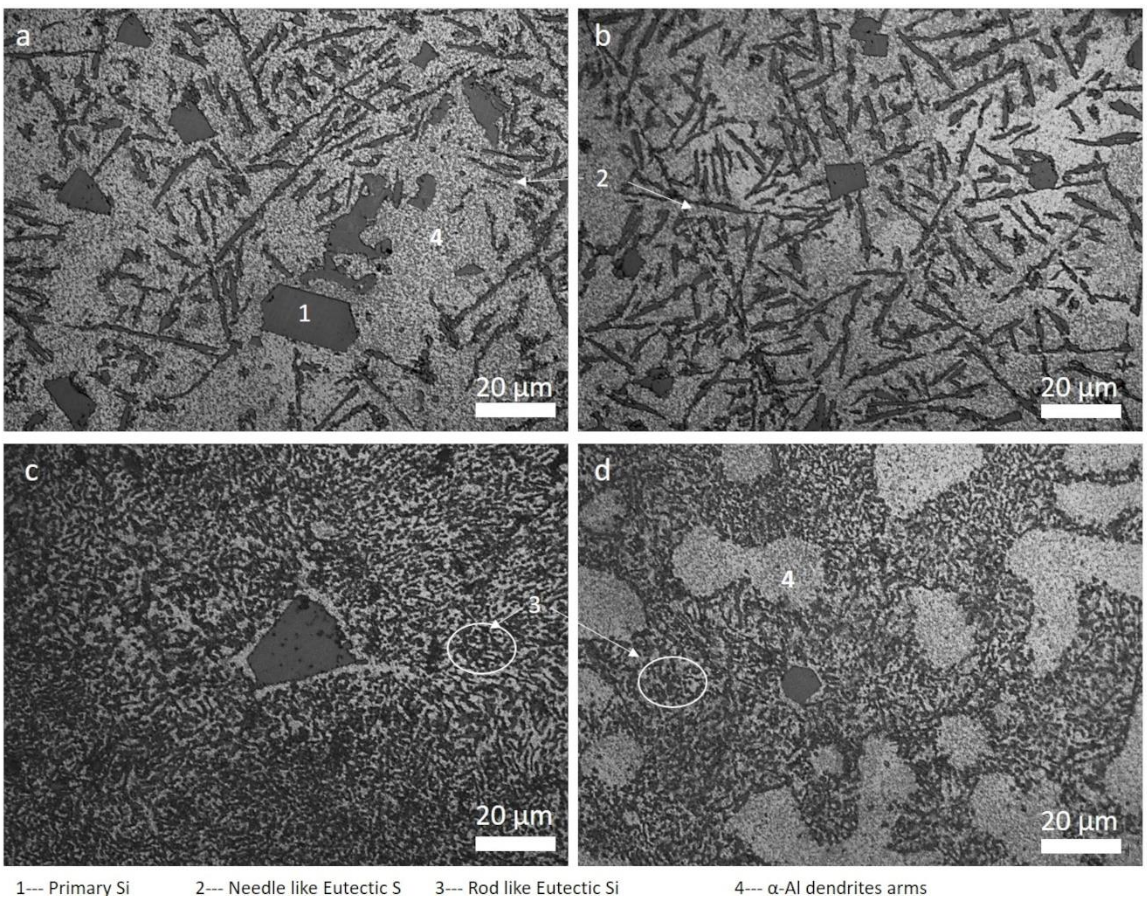


Figure 1: Optical microstructure of prepared Al-14Si alloys (a) alloy A, (b) alloy B, (c) alloy C and (d) alloy D.

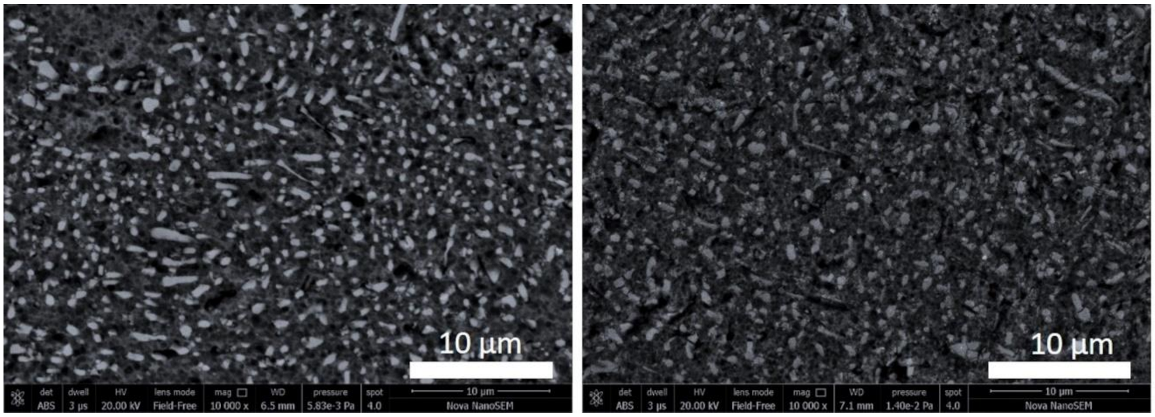
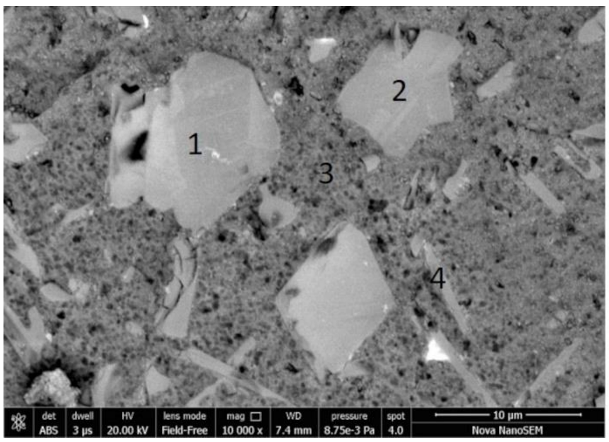


Figure 2: SEM microstructure of (a) alloy C and (b) alloy D.



Spectrum	Si	Al	Fe
1	96.65	3.19	0.16
2	95.58	4.14	0.28
3	1.98	97.81	0.21
4	90.55	9.22	0.19

Figure 3: EDS analysis of conventional cast alloy A.

Fig. 3 shows EDS analysis results of conventional cast alloy A. The results confirm that alloy consists mainly of three phases. The polyhedral shape (point 1 and point 2) is primary Si, dark grey (point 3) is α-Al phase and needle shape (point 4) is eutectic Si

In conventional casting of hypereutectic Al-Si alloys, the pouring temperature of alloys is normally 70 ^{o}C-100 ^{o}C higher than the liquidus temperature[27]. At this stage, the size and number of atomic clusters Si-Si that act as a primary Si nucleus during solidification are large. This refers to lower undercooling requirement for the nucleation of primary Si. That's why large, non-uniform, primary Si particle grows during solidification.

In MTT process, the melt is superheated above critical temperatures. At this temperature, mostly Si-Si atomic clusters dissolve in melt, and new Al-Si clusters gets formed[28]. These lead to a decrement in sizes and the total number of clusters of Si-Si in the melt, and hence higher amount of undercooling is required for the nucleation of primary Si. Furthermore, from the nucleation theory, an increase in amount of undercooling causes an increment in nucleation rate[24]. When such a melt quenched to pouring temperature with the addition of low temperature melt, the final solidified structure generates small sized primary Si and at a certain extent, refined eutectic Si[15]. When a modifier is added into melt, the growth mechanism of eutectic Si changes[12] and modifies the morphology of eutectic Si. Therefore, better refining and modification is obtained in the alloy cast with MTT along with modifier than other alloys.

3.2 Evaluation of mechanical properties

The ultimate tensile strength (UTS), elongation (EI) and hardness (HB) of Al-14Si alloys prepared under different casting conditions are presented in fig.4. The results have demonstrated that UTS, EI and HB of only MTT (B) alloy improved by 7.2%, 13.1% and 8.16%, respectively, compared to those of the conventional cast alloy (A). This is attributed to decrement in the means size of primary Si and the mean length of eutectic Si in B alloys than in A alloy. However, these properties of MTT alloy are lower than the only Sr-modified alloy (C), because of the morphology transformation of eutectic Si in C alloy. The results have also indicated that when the Sr-modifier is added during the MTT process (D alloy), an increase in UTS from 174.48 to 197.77, in EI 2.85% to 3.81% and in hardness (HB) 50.2 to 60.7 happened compared to alloy A. In the case of D alloy, primary Si refinement and modification in the morphology of eutectic Si occur simultaneously, whereas only modification has occurred in the case of C alloy. That is why the highest improvement in these properties was observed in alloy D.

As discussed in the microstructure analysis section, the MTT process significantly refine primary Si particles along with improvement in their distribution than the conventional cast process. The large sized and unevenly distributed phases are easier to crack under tensile stress than small sized phases. Moreover, the edges of primary Si particles are sharper in conventional cast alloy, which act as stress concentrator in a matrix. These lead to more brittleness in conventional cast alloys than MTT processed alloys. For these reasons mechanical properties of MTT processed alloys are better than conventionally cast alloys.

SEM images of fractured tensile test sample surfaces of various Al-14Si alloys prepared under different casting conditions are shown in fig 5. The conventional cast alloy (alloy A) fracture surface shows cleavage planes of fracture due to large primary Si and unmodified eutectic Si, which in turn creates brittleness in the alloy. The MTT processed alloy (alloy B) fracture surfaces indicate a mixed mode of fracture (dimple and cleavage) because of the presence of shorter primary Si and refined eutectic Si. The modified alloys (alloy C and alloy D) show small and uniformly distributed dimple structures compared to the unmodified alloys (alloy A and alloy B). This indicates that the ductility of modified alloys is better than unmodified alloys, which justifies the tensile test results.

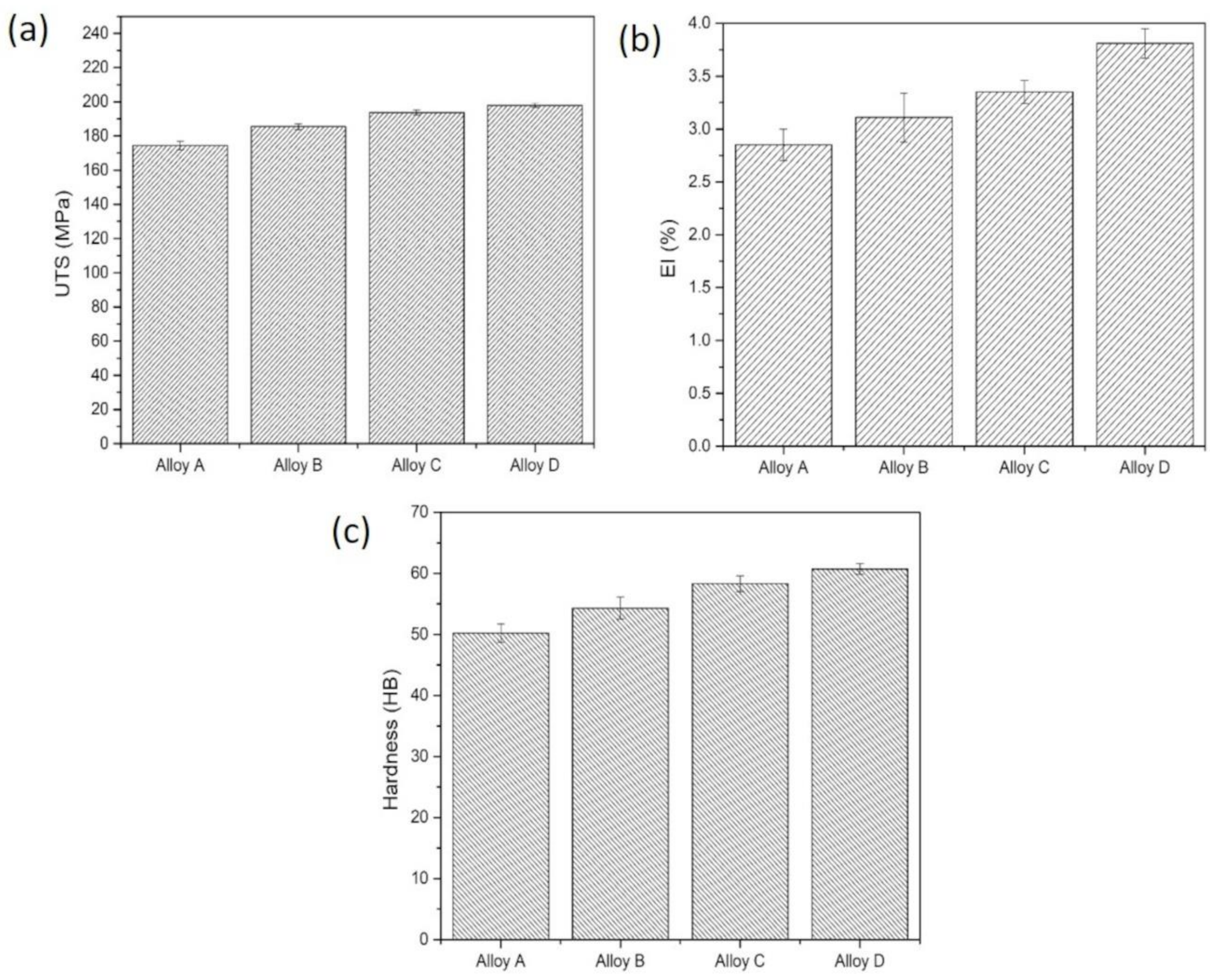


Figure 4: Variation in mechanical properties of prepared Al-14Si alloys under different casting condition.

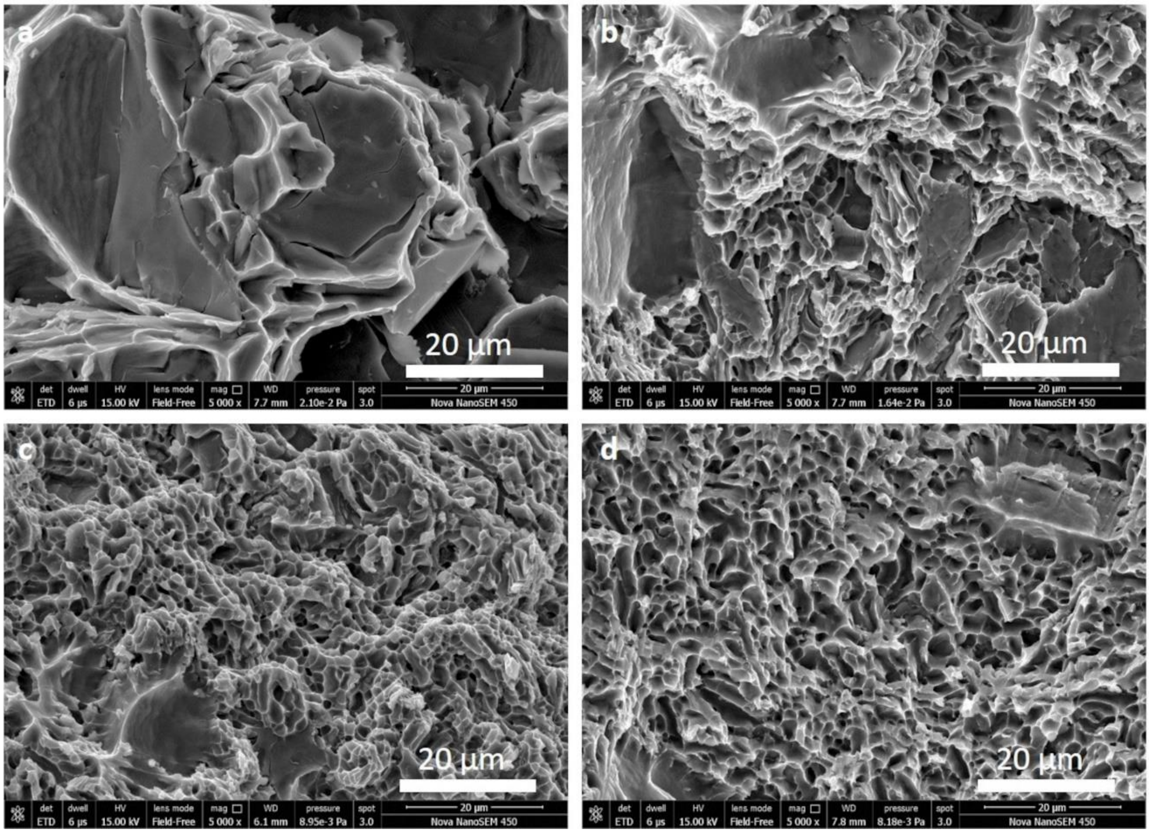


Figure 5: Fracture analysis of prepared Al-14Si alloys (a) alloy A, (b) alloy B, (c) alloy C and (d) alloy D.

4. Conclusions

1. The only MTT processed alloy reduces the size, improve the distribution of primary Si and refines eutectic Si in comparison to the conventionally cast alloy. These lead to better mechanical properties as observed in MTT alloy.
2. The MTT along with Sr modifier processed alloys have less amount of refined primary Si and modified eutectic Si. The modification effect in MTT along with Sr modifier alloy is better than that in only modifier alloy.
3. The MTT along with Sr modifier processed alloy exhibited best mechanical properties in terms UTS, EI and HB, which is 197.8 MPa, 3.81% and 60.7 HB, respectively.
4. Both Sr-modified alloys show small and uniformly distributed dimple structures compared to the unmodified alloys on the fractured surfaces.

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