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Study on microstructure, tensile, wear, and fracture behavior of A357 by modifying strontium (Sr) and calcium (Ca) content

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Abstract. Development of aluminium cast parts by stircasting technique is an effective method. Stircasting technique is one of the most commonly accepted techniques. In the present investigation, how the microstructure, mechanical and wear mechanics of A357 alloy were impacted by the presence of Sr/Ca was investigated. The outcomes revealed that addition of elements (Sr/Ca) enhance the microstructural features. Uniform dispersal of particulates (Sr/Ca) in A357 alloy and also the modified structure of silicon (Si) were observed. The outcomes also exhibited that, the simultaneous additions of Sr/Ca cause a considerable improvement of tensile strength and wear resistance. The study on fractured surfaces reveals the acceptable bonding among A357+Sr/Ca element.
Keywords: A357 alloy, mechanical behavior, wear behavior, SEM analysis

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Introduction

A357 alloy is the major alloy used for light weight metal parts because of good castability, low cost, low weight, and also exhibits better mechanical characteristics [1]. They find extensive application in aircraft/automobile products. Subsequent solidification of casting effects mechanical and wear properties of cast parts due to microstructural changes [2,3]. Mechanical strength can be enhanced by the addition of chemical modifiers generally, which cause better microstructure during solidification process. Adding of Ba, Sr, Ca, Na, and Eu, causes modification of the eutectic "Si" morphology from the coarse structure into fine fibrous structure and also a beneficial effect on ductility and material strength [4]. Though the effects of chemical modifications were known 9–10 decades back, but there was no universally accepted understanding of the mechanism that which allows the microstructure to change upon addition of little extra metal ingredient/s was available [5,6].

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In the past 55–65 years, several mechanisms of eutectic modifications were written about in the literature survey, some of them focused on the eutectic growth [7], and others on the eutectic nucleation [8]. Alloying elements like Cu and Mg, Al-silicon alloy in heat-treatment enable to attain improved mechanical and wear behavior [9,10]. Heat-treatment generally implicates an initial step where solubilization takes place. As alloying element/s solubilize in the α-Al matrix, and the second step of an artificial aging, whereas intermetallic phases nucleates into the Al matrix, thus enhancing in mechanical properties.

Some chemical elements (Sr, K, Na, Rb, Ca, La, Ce, Yb and Ba) lead to promote the modifications of eutectic Si instead of heat-treatment [11,12]. Introduction of "strontium" (Sr) leads to further refinement of the structure and enhances the ultimate tensile strength. These characteristics of the directionally crystallized alloys are greater than the eutectic alloy achieved by casting in a mold [13-15]. Sr has also been reported about modification of the inter-metallic particles which lead to high stress concentrations. Though, not all the side effects formed by addition of Sr are good. Addition of Sr was effected improved porosity with in Al-Si alloy. Sr addition has been stated to improve the efficiency of oxide inclusions within the Al melt as pore nucleation's site. The change in porosity features thus is influenced by the amount of Sr existing in the solidified structures. Porosity causes reduction in mechanical strength and leads to lower-quality of cast parts. Sr additions will also relate with grain refinements of Al foundry alloy [16-18].

In [19], the researcher studied the influence of modifying Sr in A356 matrix alloy on the mechanical behavior, and it was found that, there was an increase in the impact released energies with reduction in the grain size after the modifying of Sr element. Investigational evidence confirmed that Sr modification leads to effective due to the both quantity and quality of Sr particulates. Improved quality in mechanical properties requires a low Sr amount [20]. In [21], addition of Sr was examined in the alloy, and it was concluded that Sr causes a considerable enhancement in tensile strength compared to properties of unmodified cast part.

Beneficial application of calcium (Ca) contain modifier in Al-Si alloy, iron neutraliser in the recycled Al alloys with more iron content, scavenger of P, Bi and Sb from secondary alloy, stiffening agent in the fabrication of Al foams and also wetting promoter within the synthesis of the Metal Matrix Composite (MMCs) as an alloying elements, and calcium will impart the superplasticity [22]. The use of Ca like a modifier is presently under technical discussion, as the existence of Ca in the Al alloy may lead to negative impact. In small quantity, Ca may positively impact the subsequent alloys structure and consequently, its ensuing properties. In larger amount, Ca has an effect on undesired gasification of alloys, which leads to a rise in the porosity of a resultant structure [23]. In [24], it was concluded that, Ca can be used as significant alloying element content in Mg alloy to increase their high strength and cause better creep resistance. The researcher [25], stated that, Ca offers a thermally stabled second phase (Mg2Ca) and thus considerably enhanced the creep property and elevated high temperature strength. Al alloys with added calcium become low-cost Mg alloys which can be used as enhanced heat-resistant component in automobile applications [26,27]. It was stated that, the adding small quantity of Ca into Al alloy can lead to refinement of the grain-structures and also enhances the mechanical properties. Drits et al. [28] concluded that, addition of Ca content in Mg based alloys not only refines the microstructure, but also it improves the creep resistance and resists high temperature oxidation. In this circumstance, it is observed that, the Ca can be used like grain refiner in Al alloy material [29].

In this present work, three A357 cast parts were examined. The samples (cast parts) were examined in the unmodified and modified conditions. Alloys were prepared by stir casting method, and test samples were evaluated in terms of mechanical and wear properties to find the relationship among the modifications. Fractography and also wornout surfaces after the Sr and Ca modification were investigated. The goal of the present research work is to highlight mechanical and wear behavior A357 after Sr and Ca modification.

Fabrication of cast parts

A357 was used as a base alloy and two dissimilar modifying elements Strontium (Sr) and Calcium (Ca) were used for the fabrication of modified cast parts. In the present work, three different cast parts (A357, A357+Sr and A357+Ca) were fabricated by stir casting method. Here, the wt. % of two modifying elements was varied like 4-10 % in steps of 2 %. An electrical furnace was used to melt A357 material. After maintaining the temperature between 700-750 °C, Sr / Ca granular were added in to the melt with continuous stirring action. Stirring was maintained continuously for about 2-3 min after the addition of Sr/Ca particulates for uniform dispersal in the molten melt. Then, the melting temperature was maintained up to 800 °C for a period of 30 min, so that Sr and Ca particulates got dissolved into the molten melt. Three different cast parts such as without modifier (A357), with modifier i.e., A357+Sr and A357+Ca cast parts were fabricated by pouring of ready molten melt into the preheated mould box. The cast parts were taken out from the mold box and finally, the test specimens were machined as per the American Society for Testing and Materials (ASTM) standards*.

Result and discussion

Microstructural analysis. Uniform dispersal of modifying particulates showed an improvement in mechanical and wear behavior of produced cast parts [30,31]. A eutectic microstructure of unmodified, Sr-modified and Ca-modified alloy is depicted in Fig. 1. Microstructures of unmodified alloy depend on the inter-metallic phases and which generally depends on the alloying element. As previously stated, the Al alloys studied in this research work contain a certain quantity of Mg, Fe, and Mn. Some inter-metallic phases are noticeable by microstructure study. The amount of inter-metallic phases in the Al alloy and their effect on mechanical characteristics generally depends on the compositions of Al alloys. Some of these inter-metallic phases have proved to be detrimental, such as β-Al5FeSi, increasing in iron (Fe) content, causes reduction in elongation. Fe-β inter-metallic phases were observed in alloys. Sr / Ca significantly influence strength in developed cast parts.

Figure 1(a) shows that the Al alloy without modification of Sr / Ca had coarse microstructure, and also primary α-phase was distributed in a disorderly manner throughout the cast part. The addition of Sr causes modification of the microstructure as depicted in Fig. 1(b). Addition of Sr efficiently affects the eutectic point to a higher silicon (Si) concentration with low temperature. Eutectic points get shifted far enough to make the Al alloy, at this composition, hypo-eutectic instead of the hyper eutectic. Therefore, by adding a small amount of Sr, the microstructure of these alloys is changed, and also its properties may be significantly improved [32-34]. A small amount of Sr can bring about a change in the morphology of the eutectic silicon phase which causes a change in Al alloy from the coarse structure to a fine fibrous structure. When "Ca" was modified in the Al alloys as depicted in Fig. 1(c), structure was developed, and it was observed that, the primary α-phase dendrites were reduced. When Ca was added, the best refinement in the microstructure in Al alloy was observed. And also the primary α-phase with the smallest dendrite size, which was settled regularly within the base alloy, was seen. By Ca addition, the microstructure of the Al alloys started to deteriorate.

*(ASTM standards web-link for tensile test specimens: https://www.trl.com/astm_e8_tensile_testing_of_metals/) and (ASTM standards web-link for wear test specimens: https://www.astm.org/g0099-17.html)

The primary dendrite of a primary α-phase becomes coarse. So, the size of the primary α-phase dendritic was very small, and also it is in uniform distribution [35]. The importance of adding Ca to A357 at casting conditions generally helps to improve the mechanical properties and reduce the corrosion rate. In the present research work, A357 alloy with Ca addition leds to reduce the growth of dendetic structures, which results in improvement of mechanical and wear properties.

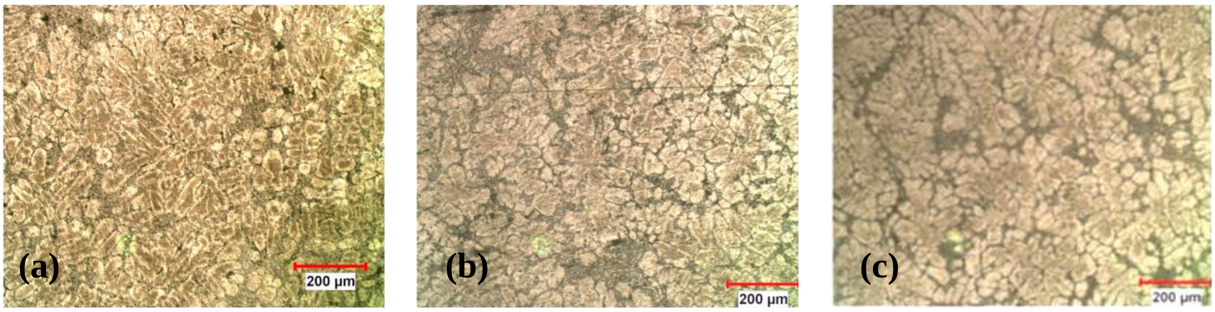

Fig. 1. Microstructure images of (a) A357 (b) A357+Sr (c) A357+Ca

Tensile strength. Influence of modification as regards the tensile strength of Al alloys and simultaneously modified Sr and Ca cast parts are shown in Fig. 2. It is found that the tensile strength of unmodified is lower than that of simultaneously modified Sr / Ca cast parts. Similar variation in UTS of such developed cast parts fabricated by stir casting was observed [36]. Interesting outcomes were achieved from the simultaneous addition of Sr / Ca, as depicted in Fig. 2. Enhancement in tensile strength of the developed cast parts maybe related to the modified elements, which increase particulates wettability in alloy. So, it was predictable that the modifiers would show significant variations on percentage of elongation. Since, chemical modifications could form tiny and round Si crystal due to the phenomena of fragmentation. The existence of tiny and round Si particulates reduces the stress concentration in alloy and consequently increases ductility during the plastic deformations [37-39].

The changes in microstructure due to Sr modification produce an enhancement in the tensile strength of the alloy cast in sand / metal moulds. Sr particulates were also applied to transform the platelet Fe-rich phases to an AlFeSi. The addition of Sr promoted the development of a-AlFeSi and also improved the extrusion characteristics considerably, especially tensile strength. It was also observed that, the material properties were improved by the addition of Sr into Al alloys. Fe is one of the alloying elements in A357. Fe-rich intermetallic phases have much more multifaceted morphologies, with brittle and fragile appearance. The existence of Fe is usually reported to have a detrimental effect on strength, ductility, and fatigue properties of Al alloys. After modifying Ca content, the tensile strength of the developed cast part was enhanced when compared with the tensile strength of unmodified cast part. The development observed was attributed to the corresponding enhancement in grain refinement [40]. Whereas, the tensile strength of A357+Ca cast parts is lower when it is compared to the tensile strength of A357+Sr cast parts. Similar outcomes were also observed from other researcher [36]. But at 10 wt.% of Sr and Ca content, led to reduction in the tensile strength due to agglomeration effects [41,42].

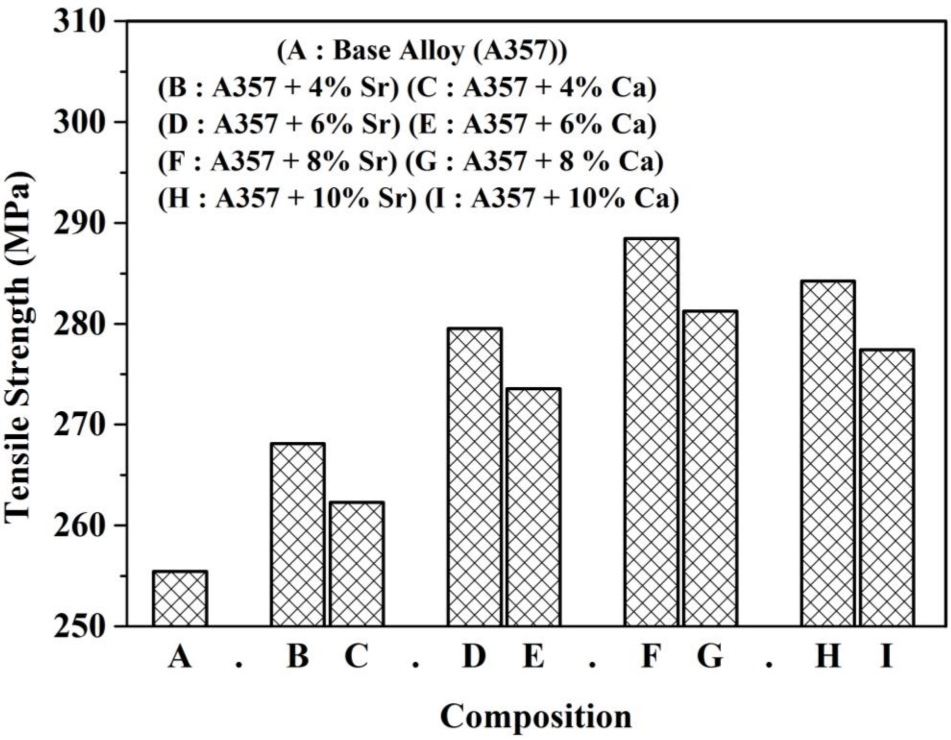

Fig. 2. Tensile strength for A357 and varying wt. % of Sr and Ca

The stress-strain graphs of A357 alloys and simultaneously modified Sr/Ca cast parts are depicted in Fig. 3. Mainly, these stress-strain curves show that, tensile strength is enhanced when fracture strain is reduced by increasing the content of modifying elements. It is found that, the unmodified alloy (A357) has the high plastic strain rate and also exhibits lowest resistance for plastic deformation when compared with A357+Sr and A357+Ca cast part. It is seen that the modified cast parts exhibit improved strength when it compared with unmodified alloys (A357).

Generally, this is caused by better grain refinement and also strengthening of particulates. The enhancement of material strength in the element modified cast part is generally due to mismatch strengthening and also high load bearing capacity produced by the Sr/Ca particles. Because of the thermal-mismatch stress, there is a tendency to rise in dislocation of density in the base alloy as it cools from solidification temperature. The dislocation results in stress at an interface of particles and the base alloy. This stress usually depends on the temperature from which the developed cast parts were cooled. High temperature causes increased stress at the interface. This makes the plastic deformation very hard and results in improved strength of cast parts.

As compared to the base alloy, the enhancement in the material strength of modified cast parts is generally due to existence of the hard particles (Sr/Ca) which restrict the motion of dislocations within the alloy. Increasing in wt. % of Sr/Ca particulates content might increase dislocation density with in the Al alloy, which is called as the dislocation strengthening. These dislocations trapped by the Sr particulates lead to improved tensile strength of the developed cast parts as compared to Ca modified cast parts.

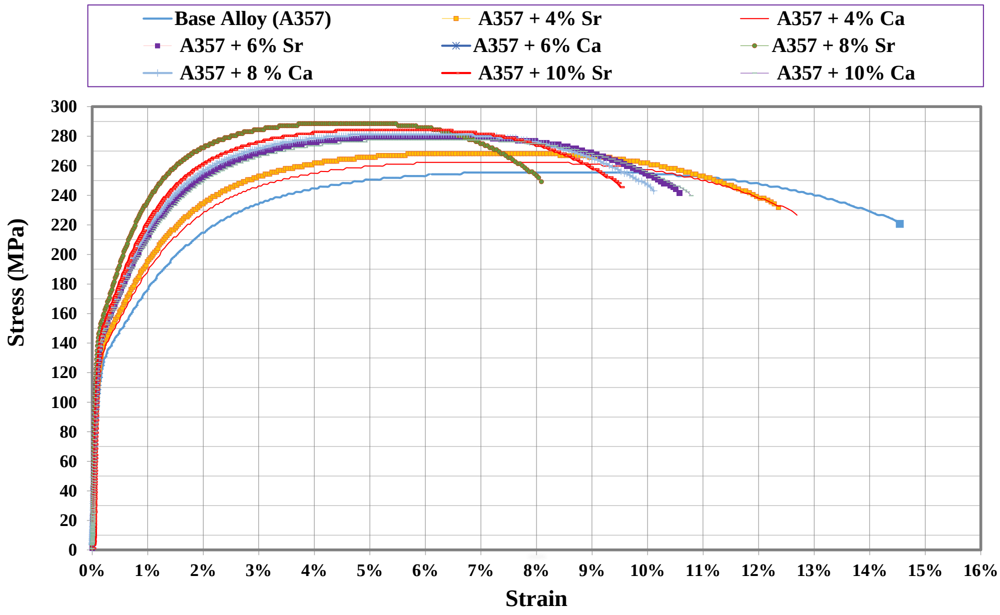

Fig. 3. Stress strain curve of A357 and varying wt. % of Sr and Ca cast parts

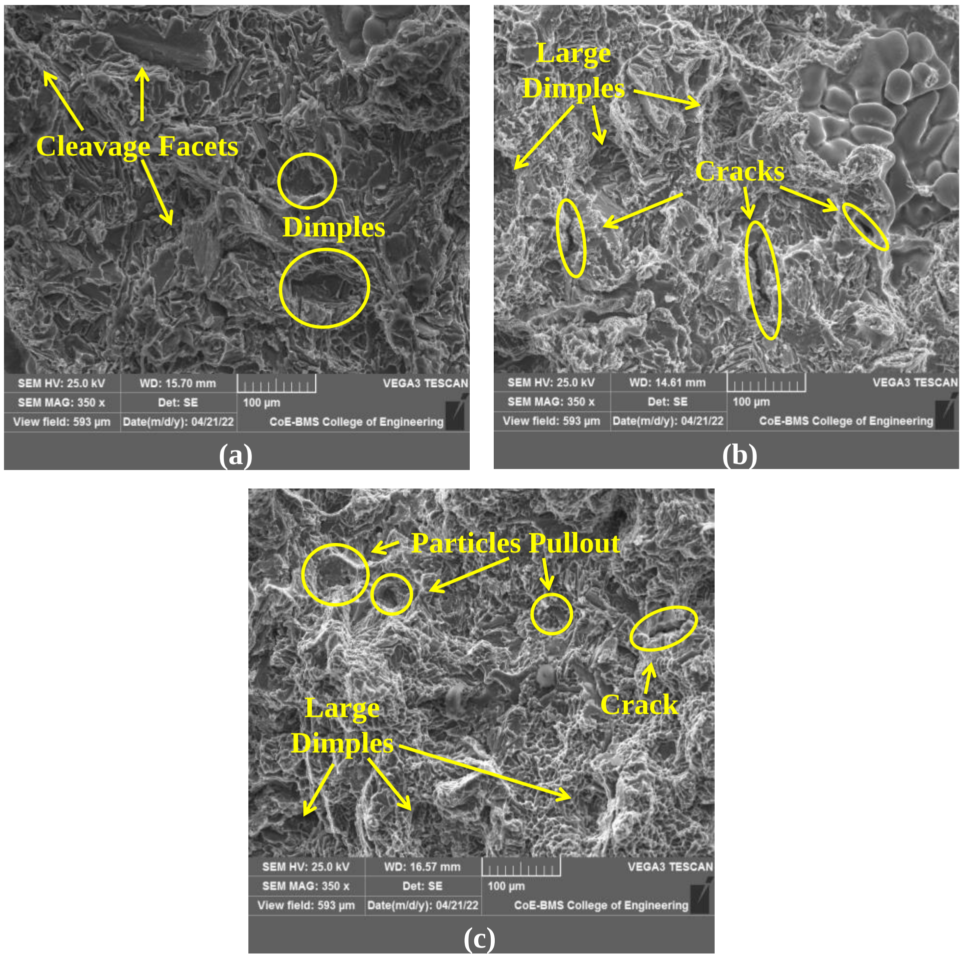

Fig. 4. Fracture images of (a) 357, (b) A357+Sr and (c) A357+Ca

A fractured surface of the tensile test specimen was examined to study the failure mechanisms of the developed cast parts. Figure 4(a) depicts the fractured surface of unmodified alloy (A357). Fig. 4(b) depicts the fractured surface of A357+Sr modified cast part. Figure 4(c) depicts the fractured surface of A357+Ca modified cast part. The extent of cracking is high in the test samples modified by the Sr/Ca. This indicates the strong bonding at the interface. In-fact, when the interface is very strong with an alloy, the Sr/Ca gets loaded to their fracture crack. Relatively a large number of broken / cracked surface are seen in the case of addition of Ca/Sr, and this number is less in unmodified test samples, as shown in Fig. 4 (a) and similar results were observed in [36]. The fractured surfaces show that the unmodified alloys are brittle in nature of fracture, which follows the eutectic Si modules and are further improved by contribution due to iron-rich phase. Whereas, the modified alloys have a nature of ductile fracture. Generally, this follows largely through the plastic deformation of Al alloy [43].

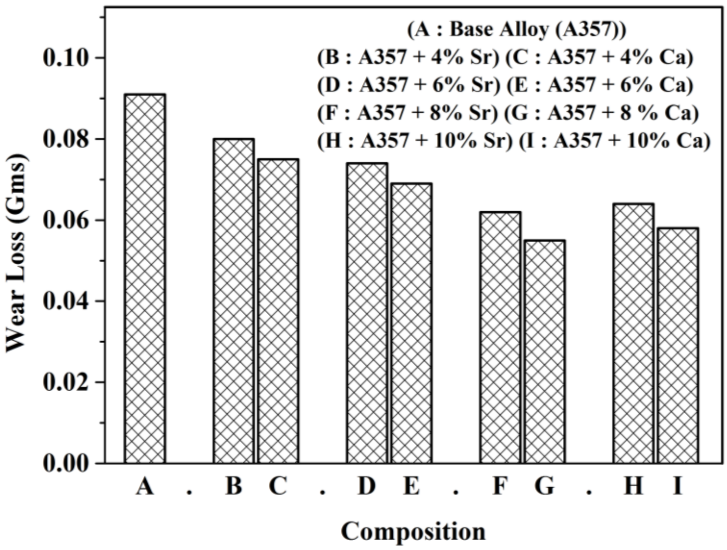

Fig. 5. Wear loss of A357 and varying wt. % of Sr and Ca

Wear loss. Wear behavior was evaluated as per ASTM standards at a constant speed (sliding speed) of 2 m/s and 20 N of load against a steel disc (grade: EN-32). Test samples of 30 mm length and 8 mm ϕ were prepared by CNC machining as per the ASTM standards. The amount of wear loss of the developed cast parts were calculated by weight loss method. Figure 4 depicts the wear loss of all the developed cast parts. From the Fig. 5, it can be seen that, the wear loss of A357 alloy was high when it is compared to the cast parts of A357+Sr. But whereas, the wear loss of A357+Ca cast parts was again high when it is compared to cast parts of A357+Sr. By adding Sr content, the granular eutectic silicon phases are uniformly dispersed in aluminium dendrite boundaries. Fe-rich phase is entirely refined and also distributed within the centre of the silicon phase. So, the stress concentration among the secondary phase, substrate is also lessened and the adhesion between the secondary phase & substrate can be significantly enhanced and this led to better wear resistance. A357 with appropriate wt. % of Sr effected improvement of wear resistance when compared to the cast parts without Sr modification. Though, too hard and brittleness can also lead to deterioration of the wear resistance [44].

From Fig. 5, it is evidenced that the wear loss considerably decreases at initially and further increases due to increase in Sr content. This is mainly coincident with changing the trends in average size of the primary Mg2Si phases of the base alloys [45]. Ca modified cast parts have higher wear resistance compared to unmodified cast parts. Further, wear resistance of A357+Ca have been reduced compared to A357+Sr. Similar outcomes have been found in [36] and also stated that, increase in wear loss at higher wt. % of modifying elements is generally due to the agglomeration effect [42,46].

COF (μ). The coefficient of friction (COF) of the alloy and modified cast parts are shown in the Fig. 6. The average value of COF of A357 without Sr/Ca is found to be highest. By increasing in Sr content, the average value of COF of the A357 alloys become less. On addition of Sr content, the average COF of alloy reaches the minimum value. Friction arises as due to bonding of surfaces, the molecules on both the surfaces bond with each other, also resists when the surfaces try to move away and break the bonding. As stated, when the content of Sr content is increased, the wear loss is minimum. Consequently, the amount of wear debris accrued, among asperities, is also significantly reduced. At constant applied load, reduced COF would generally lead to the lower friction factor [44]. Ca modified cast parts showed improved COF compared to unmodified cast parts. But whereas, compared to Ca modified cast parts, A357+Sr cast parts exhibit improved COF.

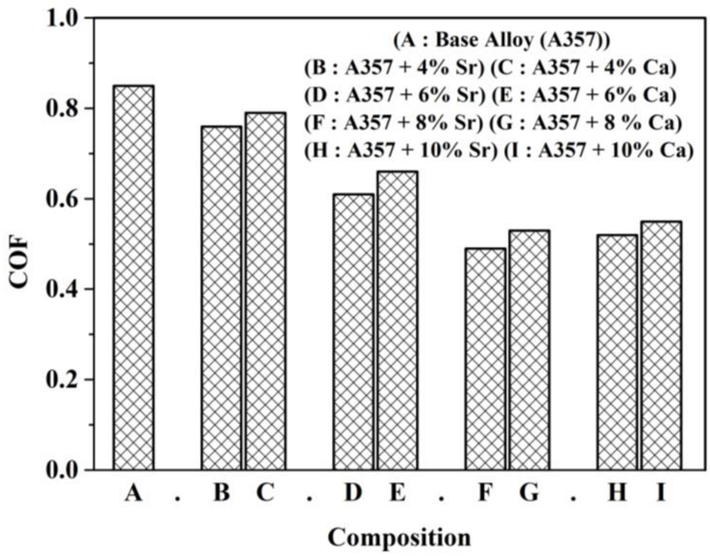

Fig. 6. COF of A357 and varying wt. % of Sr/Ca

The wornout surfaces of A357 alloy and other cast parts of varying wt. % of Sr/Ca content are depicted in Fig. 7. A thick oxidation film is deposited on the surface of Al alloy at room temperature (27 °C). Mainly, when subjected to higher loads, released heat and the surface roughness cause formation of oxidized films on grinding surface of Al alloy. Due to the presence of lubricant, the oxide film direct interaction between the base alloy and hard disk is prevented. So, oxide films not only decrease the COF but also increase wear resistance. Though, under adequate normal force, the plastic deformation will take place on surfaces of the base alloy, which generally results in formation of the cracks in the oxide film layer. It can be seen in Fig. 7(a), that a plastic deformation ensued, and parallel scratch marks are created due to rubbing action between hard spots of friction pairs. In Fig. 7(a), larger pits are seen at sliding surfaces. It indicates that, delamination wear was caused in wear test trails. Delamination wear is a fatigue wear, affected due to frequent sliding wear of base alloy. It is also observed that, the flake cracks are formed in surface layer as also developed in the subsurface. Numerous cracks propagated to the wear surface leads to peeling of material. Because of the brittle nature, generally the oxide film gets broken when the Al alloy crosses its load limits of the external forces. So, the softer Al alloy and friction pair contacts between each other directly, which results in the high wear loss [44].

Compared with one in Fig.7(b), the peeling pit in Fig. 7(c) has wider and deeper scratches. With additional Sr content, eutectic silicon and also Fe-rich phases have granular shape, which generally causes tight adhesion between the alloy and secondary phase. It not only prevents grain boundary from the sliding, but also avoids the shear effect between the soft base alloy and hard asperity, and it reduces the generation, growth, and expansion of the crack. Addition of Sr content can modify the alloy microstructure to improve the material strength. So, the scratches on the wear surface of A357+Sr in Fig. 7(b) are finer when compared to the A357 without Sr addition in Fig. 7(a). As depicted in Fig. 7(b), almost no peeling pit or plastic deformation is found on the wornout surface of A357 alloy modified with Sr content.

Figure 7(c) depicts the wear debris produced from the wear tests of A357 alloy modified with Ca content. According to the wornout surface images, it is seen that, the size of debris belonging to A357+Ca is very much smaller as compared to that of unmodified A357 alloy [44]. The ground surfaces are less damaged than the unmodified test samples.

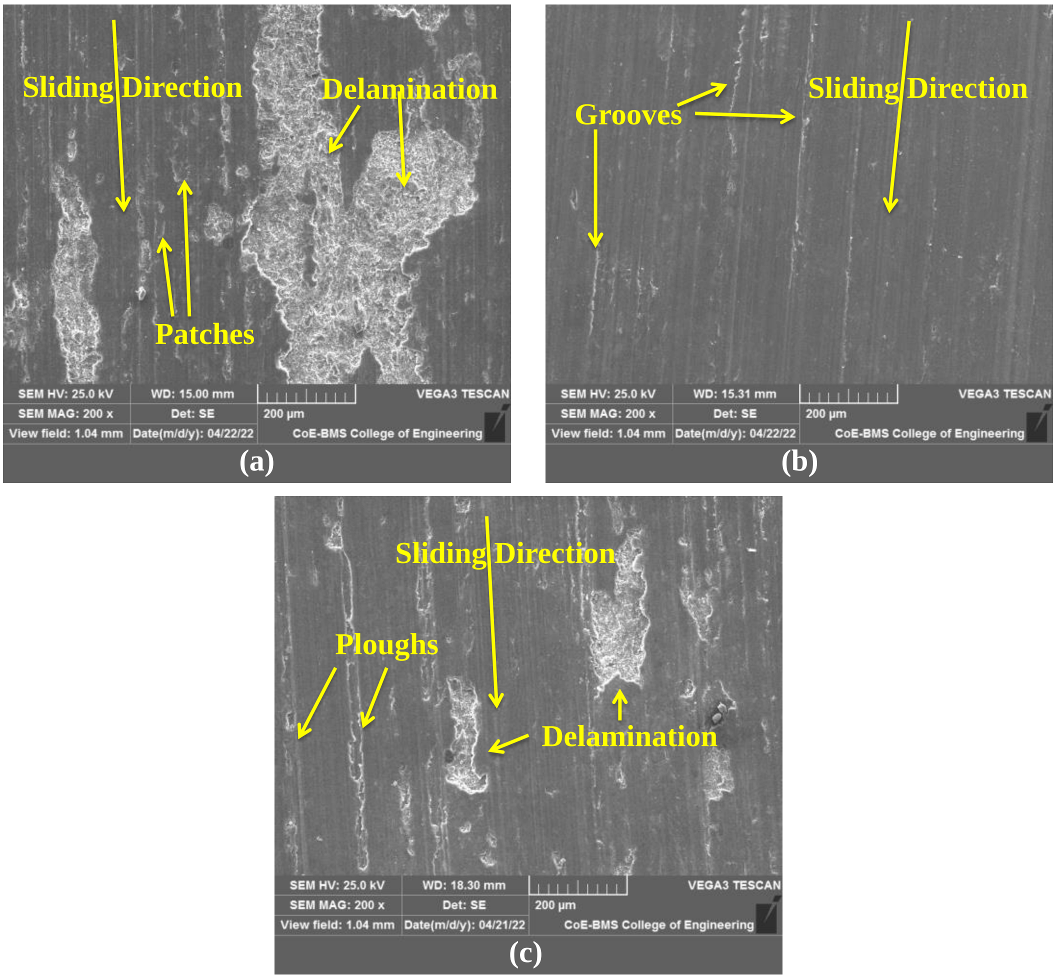

Fig. 7. Worn-out surface morphology of (a) A357, (b) A357+Sr, and (c) A357+Ca

Conclusions

A357-Sr/Ca cast parts were produced by stir casting method. Different wt.% of Sr and Ca (4, 6, 8 and 10 %) were added (modified) to A357 alloy to achieve optimum levels of Sr and Ca on the microstructural amendment. Further, the study was undertakes to examine the mechanical and wear behaviour of developed materials by modifying with Sr and Ca.

Acceptable fibrous structure of silicon crystals in the alloy is attained by modifying Sr content, but high content of Ca is required for modification of the A357 alloy to achieve similar improvement of structure. Additions of Sr or Ca content enhance the tensile strength of A357-Sa / Ca cast parts to some extent. But at higher wt.% of Sr / Ca it led to reduction in the material strength due to the agglomeration effect. Ca modified cast parts have higher wear resistance than the unmodified cast parts. Further, wear resistance of A357+Ca cast parts is less when compared to wear resistance of A357+Sr cast parts. Ca modified cast parts show better COF compared to unmodified cast parts. But compared to Ca modified cast parts, the A357+Sr cast parts exhibit better COF. From the SEM images of fractured surfaces, the fracture like brittleness is observed in A357 (unmodified) cast part samples. The wear mechanism of examined alloys is a mild abrasive oxidative wear with the little adhesion.

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