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Study on Partial Replacement of Silica Sand With Alternatives and Its Effect on Sand Mould and Casting Properties

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Abstract

In the current scenario the demand for reduction of silica sand usage in making sand moulds in the metal casting industry is increasing day by day. The non-silica alternatives will help the foundries to not only get in line with new regulations but also protect the foundry workers and minimizing the compliance costs. The non-silica alternatives such as clay, bio-waste, bagasse-ash and nano-SiO_2 in different proportions are added to silica sand to prepare moulding sand. The effect of these alternatives on mould sand properties such as permeability, green shear strength and green compression strength are studied. The aluminium alloy 6061 castings were fabricated in the sand mould prepared using these non- silica alternatives. Effect of these materials on the grain size, surface roughness and mechanical properties of aluminium alloy 6061 castings were studied. Out of all, the silica sand/15%bagasse-ash combination was found more suitable for producing aluminium alloy 6061 castings with high yield strength, ultimate tensile strength and low surface roughness values. The ranking of combinations based low surface roughness and high strength values of aluminium alloy 6061 castings is, bagasse-ash > bio-waste > nano-SiO_2 > clay.

Keywords: *Aluminium Alloys, Mechanical Properties, Moulding Sand, Permeability*

1. Introduction

Metal casting industry is the backbone of manufacturing economy in most of the developed as well as developing countries. With ancient routes, this highly modern industry with turnover over several hundred billion dollars is providing job to several million people across the globe. The different industries like construction, mining, automotive, wind turbines, aerospace, defence, medical and nuclear plants employs components/structures made up of castings. Interesting fact to be noted is that almost all manufactured goods at least one part which is made by metal casting process. In the year 2017 about 10.7 million tons of casting products were fabricated in United States alone. By employing 490,000 people the metal casting industry has fabricated $44.3 billion worth castings in the United States in the year 2019. The Modern Castings, USA provided a global scenario pertaining to metal

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casting industry by publishing 53rd World casting census. According to census the global casting production was about 112.7 million tons and China being the largest casting producer followed by India and USA. The Indian metal casting industry has about 5000 units all over the country and out of which about 90% are classified as micro, small and medium enterprises. At present as many as 50000 to ~1.5 million people were employed directly or indirectly and showed the capability of additional employment of roughly 2 million in the next decade. From this one can see the enormity of metal casting industry and its importance to modern infrastructure and growing economy (A Modern Staff Report, 2019; Foundry Informatics Centre, n.d.).

In sand moulding process the molten metal is poured into the sand mould which contains cavity of a component of required shape and size is carved in it. It is the least expensive and most commonly used casting technique which is capable of producing better casting dimension tolerances with good surface finish. The sand mould is made up of silica sand (85%-95%), bonding agent (7%-10%), additives of carbon (~5%) and water (2%-5%). The main component, silica sand is extracted from beaches/ ocean beds, river beds and inland dunes. The chemical composition of the sand is highly dependent on the source of extraction and in order to have high quality castings the SiO_2 content in the sand should be more than 87%. The second ingredient of the sand mould is the bonding agent which provides the sand strength and moldable characteristics. Clay based materials like bentonites and montmorillonite are used as bonding agents because of their high durability under application of heat and higher bonding strength. In certain cases the carbon based additives such as coal dust is added to the sand in order to improve the quality of castings. Finally water is added and is mulled into the clay so that it acts as bonding agent for the sand grains. However apart from SiO_2 content the properties of green sand are dependent on the type of binder, additives, sand particle shape and size (Kapranos *et al.*, 2014; Sahoo and Sahu, 2014; Adedayo, 2010).

About million tons of foundry waste is generated every year across the world which majorly includes silica sand. The silica sand used for casting process become unusable after single or multiple uses and has to be discarded for further usage and is termed as foundry waste. The reasons for discarding silica sand are, lowering of resistance of sand grains due to abrasion, exposure of sand grains to very high temperatures of 1500°C, physical and chemical degradation of sand grains. Most of silica sand is disposed of to a landfill after usage but this is taking a huge toll on environment. This is because the discarded sand also contains binders which are insoluble in nature. It is observed that virgin sand after use is sent to regeneration plant for treatment after which it is sent back to foundries again for casting purpose. During this process about 13 million kilos of carbon dioxide is released in to the atmosphere which indeed puts a huge burden on the environment. The high disposal cost and filling landfills have necessitated a proper solution for either reduction in consumption of silica sand or have solid recycle or regeneration units. Further, reduction in silica sand consumption can be helpful in spared landfill, no need to pay hefty for disposal, reduced effects on both human beings and environment and preservation of natural resources. In such a scenario there are few solutions, one is minimization in silica sand consumption by adding additional material, second is reuse the same sand multiple times and third utilization of discarded sand in some other construction industry. Several groups in India are actively trying to work on quarry dust as potential mould material especially for making aluminium castings. Usage of quarry dust will not only help in replacement of silica sand but also help in minimizing the environmental impact of mining and the waste generating from it. Although the alternative materials are being suggested but there are certain concerns which need to be addressed properly to obtain a good quality moulding material. Partial or complete replacement of silica sand with non- silica alternatives will help the foundries to not only get in line with new regulations but also protect the foundry workers and minimizing the compliance costs (Davis, 1979; Modern Castings, 2019; Prabhushankar, 2020). For instance, Murthy *et al.* (2016) studied the properties of mould made up of high carbon ferro chrome slag. The suitability of slag as mould material was studied by subjecting mould to compression strength, shear strength and permeability. The test results showed properties equivalent to silica sand and suitable to produce aluminium castings. Siddharth *et al.* (2020) explored the possibility of using banana peel powder as additive material for making green sand. The results obtained suggested 3% banana peel powder was ideal additive along with 7% bentonite and sand. Beno *et al.* (2021) proposed alumino silicates as an alternative mould material for making iron and steel castings. This material showed similar heat resistance, lower coefficient of thermal expansion and better surface casting quality when compared with conventional chromite sand. It can be observed that various materials are being tried for possible replacement of silica sand for making sand mould. In the light of above, this work is focussed on partial replacement of silica sand with clay, bio-waste, bagasse-ash and nano- SiO_2. The novel mixture of green sand was subjected to permeability, shear strength and compression strength studies. Further the sand mould prepared using these different combinations were used for making 6061Al castings. The effect of sand mould constituents on grain size, surface roughness, microhardness and mechanical properties were studied.

2. Experimentation

In this work, clay, bio-waste, bagasse-ash and nano-SiO_2 powders were used as non- silica alternatives to the mould sand. All these powders were procured from the local suppliers and were added to the silica sand in different weight percentages of 5% to 15%. Total of 12 combinations were prepared by mixing silica sand/x (x - clay, bio-waste, bagasse- ash and nano-SiO_2 powders), bonding agent and water. All these materials were mixed using sand muller and the resulting mixture was rammed using sand rammer. The properties of the mould sand like permeability, green shear strength and green compression strength were evaluated as per American Foundry Society (AFS) standards. In order to obtain the permeability number the procedure mentioned by Seidu *et al.*(2014) was followed.

The shear strength test was conducted using appropriate testing fixtures and the stress required to cause the shear was noted as green shear stress. The compression strength test was carried out on rammed samples using universal testing machine. The compressive loads were applied on samples until it failed and the load which caused the failure was recorded. The equipment's used for permeability and compression test are shown in Figures 1(a) and (b). The quality of the mould and its effect on surface roughness and mechanical properties of the casting were investigated. This Al-Mg-Si-based alloy, 6061Al, was chosen, and ingots of this alloy were melted in a graphite crucible. A melting temperature of 800°C was chosen, and hexachloroethane tablets were used to degas the molten metal. After the melting process was completed, the molten metal was poured into moulds and allowed to cool at room temperature. Surface roughness was applied to the castings in order to determine how different combinations of mould sand affect the quality of 6061Al castings. All castings were tested according to ASTM standards to determine grain size, microhardness, and mechanical properties.

3. Mould Properties

Let's see the sand mould properties such as permeability number, green shear strength and green compressive strength are listed in Table 1 for all non-silica based additives at different weight percentage in the silica sand.

The multiple numbers of tests are conducted because whenever additives are used in silica sand, the attention should be paid on both permeability and strength. The

(a) (b)

Figure 1. Equipment's used for testing properties of mould sand. **(a)** Permeability test **(b)** Compression test.

Table 1. Mould sand properties for different weight percentage of non-silica additives

Non-Silica additives	Wt% in sand	Permeability	Shear Strength (gm/cm^2)	Compression Strength (gm/cm^2)
Clay	5	61.2	120	320
	10	52.3	145	340
	15	39.8	180	360
Bio-waste	5	52.1	142	310
	10	43.5	161	340
	15	41.2	170	365
Bagasse Ash	5	70.5	155	340
	10	61.7	188	370
	15	49.9	205	390
Nano-SiO_2	5	62.5	110	290
	10	48.8	165	315
	15	43.7	190	320

permeability number was found to decrease with the increase in non-silica additive content. Take for instance the silica sand/x%clay sand mould showed decrease in permeability number from 61.2 to 39.8 when the clay content is increased from 5% to 15%. With increase in bagasse ash content from 5% to 15% the permeability number decreased from 70.5 to 49.9. The drop in permeability number for silica sand and Fe-Cr slag based mould was reported by Murthy and Rao (2017). With increase in both sodium silicate content and CO_2 gassing time, the permeability number for both types of mould was decreased. So the drop in permeability number in present case could be attributed to closure of pores between the silica sand particles due to increase in non-silica additive content. Initially these angular shaped non- silica additives are trapped inside the pores between the silica sand particles and close them when their weight percentage is increased from 5% to 15% leading to considerable in permeability number. All non-silica additives showed high permeability number when there weight percentage was 5%. Out of all, the silica sand/x%bagasse ash mould showed higher permeability number while silica sand/x%bio-waste sand mould showed lower permeability number. In order to escape the entrapped gases or generated during interaction between molten metal and mould, the sand mould need to have higher permeability. If the sand mould doesn't allow these gases to escape then there are high chances of formation of defects such as pores in the castings (Ajibola *et al.*, 2015). In present case high permeability number for silica sand/x%bagasse ash sand mould means it is better in allowing the gases to escape then other combinations. The shear strength on the other hand was found to increase with the increase in weight percentage of non-silica additives. In case of silica sand/x%bagasse ash sand mould the shear strength was found to increase from 155 gm/cm^2 to 205 gm/cm^2 as the weight percentage were increased from 5% to 15%. Similarly the shear strength of silica sand/x%nano-SiO_2 sand mould was increased from 110 gm/cm^2 to 190 gm/cm^2 as their content increased from 5% to 15%. Out of all, the silica sand/x%bagasse ash sand mould showed higher shear strength values while silica sand/x%clay sand mould showed lower shear strength values. Finally the sand mould property evaluated for all combinations is compressive strength. The compressive strength of silica sand/x%bagasse ash sand mould was increased from 340 gm/cm^2 to 390 gm/cm^2 as their content increased from 5% to 15%. In case of silica sand/x%nano-SiO_2 sand mould the compressive strength was found to increase from 290 gm/cm^2 to 320 gm/cm^2 as the weight percentage were increased from 5% to 15%. Out of all, the silica sand/x% bagasse ash sand mould showed higher compressive strength values while silica sand/x%nano-SiO_2 sand mould showed lower compressive strength values. Better compressive strength is due to good ramming and compaction of sand mould however better in particular the silica sand/x% bagasse ash sand mould showed higher value which is attributed to fine size of bagasse ash. This is mainly because the strength of sand mould depends on the surface area of constituents of mould sand. Higher the surface area better will be strength as more number of sand grains is available for bonding. Compared to all other non-silica additives, the bagasse ash particles have very fine size due to which the specific surface area is very high and this makes it very for them to interact with the surrounding sand grains. The bagasse ash particles possess high surface area and these fine grains develop higher compressive strength than coarse grain size additives (Zhuang and Chen, 2019). The observation on increase in shear and green compression strength with the increase in non- silica additive content is well in line with the work reported by Okonji *et al.* (2018) on ground nut shell ash and ant hill based mould sand. The authors showed that with the increase in both of these additives, both shear and green compressive strength were increased. The high strength values observed in the present work will be very effective in obtaining defect free and sound 6061Al alloy castings.

4. Casting Properties

The surface roughness, grain size, microhardness and mechanical properties of cast 6061Al alloy in different sand mould combinations are presented in Table 2. First let's see the surface roughness of 6061Al alloy castings fabricated in different sand mould combinations. The surface roughness (R_a) of 6061Al alloy castings fabricated in different sand mould combinations is listed in Table 2. In case of 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould the surface roughness was found to decrease from 2.95 to 2.73 as the weight percentage were increased from 5% to 15%. The surface roughness of 6061Al alloy casting developed in silica sand/x%nano-SiO_2 sand mould decreased from 3.85 to 2.82 as its content is increased from 5% to 15%. Out of all, the 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould showed lower surface roughness values while the 6061Al alloy casting developed in silica sand/x%clay sand mould showed higher surface roughness values. The grain size of 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould decreased from 41 μm to 38 μm as its content is increased from 5% to 15%. In case of 6061Al alloy casting developed in silica sand/x%nano-SiO_2 sand mould the grain size was found to decrease from 64 μm to 53 μm as the weight percentage were increased from 5% to 15%. Out of all, the 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould showed lower grain size values while the 6061Al alloy casting developed in silica sand/x%nano-SiO_2 sand mould showed higher grain size values.

The microhardness of 6061Al alloy castings fabricated in different sand mould combinations is listed in Table 2. In case of 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould the microhardness was found to increase from 65 VHN to 73 VHN as the weight percentage were increased from 5% to 15%. The microhardness of 6061Al alloy casting developed in silica sand/x%clay sand mould increased from 58 VHN to 66 VHN as its content is increased from 5% to 15%. Out of all, the 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould showed higher microhardness values while the 6061Al alloy casting developed in silica

Table 2. Mechanical properties, surface roughness and grain size of aluminium casting

Non-Silica additives	Wt% in sand	Yield strength, MPa	Ultimate tensile strength, MPa	Vickers Hardness	Surface Roughness (Ra)	Grain size (Microns)
Clay	5	78	170	58	3.7	58
	10	81	174	64	4.8	56
	15	86	182	66	4.65	53
Bio-waste	5	80	175	62	3.2	54
	10	84	187	65	3.15	52
	15	88	189	73	2.93	48
Bagasse ash	5	94	171	65	2.95	41
	10	106	182	71	2.84	40
	15	114	199	73	2.73	38
Nano-SiO_2	5	83	153	58	3.85	64
	10	94	172	63	2.91	57
	15	110	185	69	2.82	53

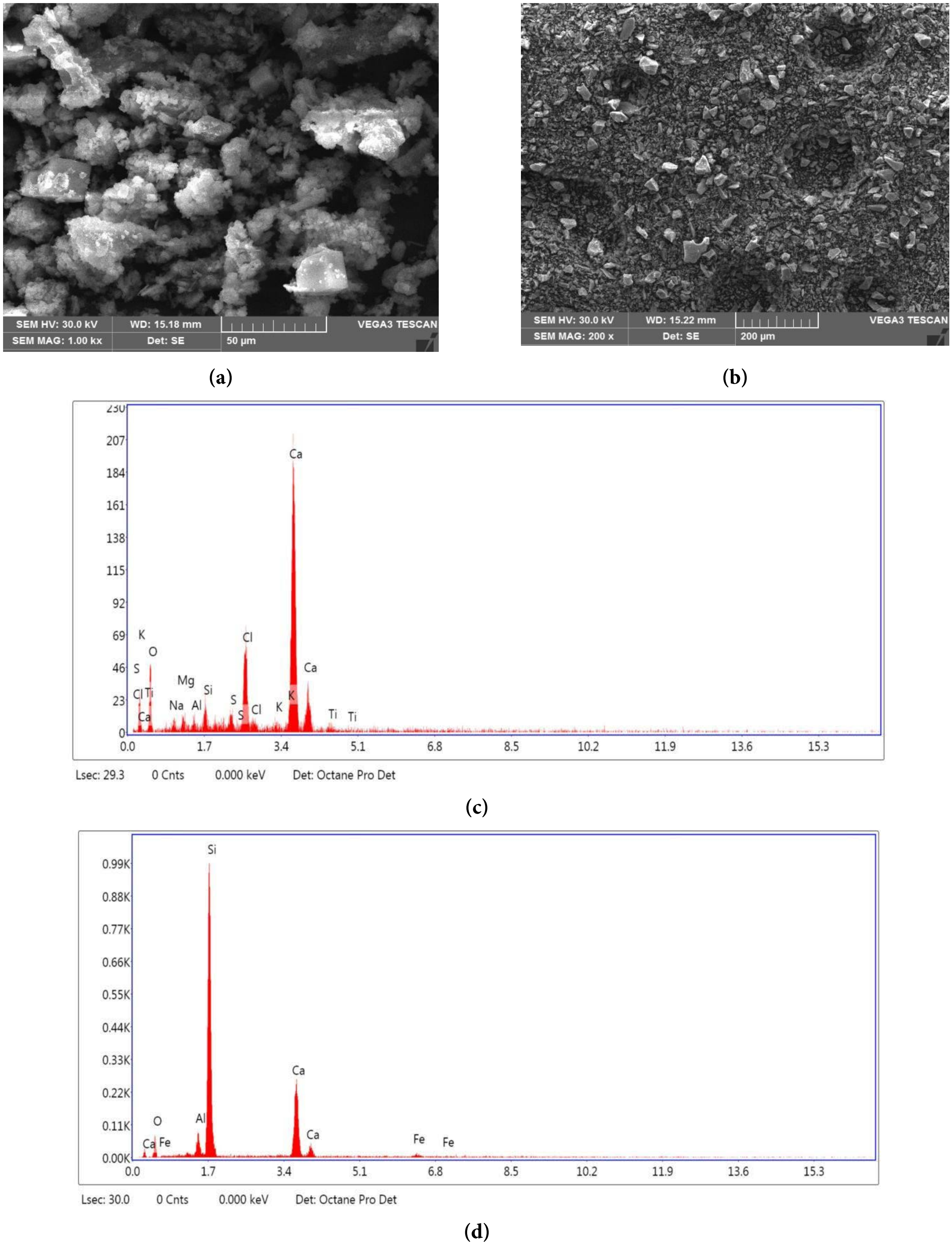
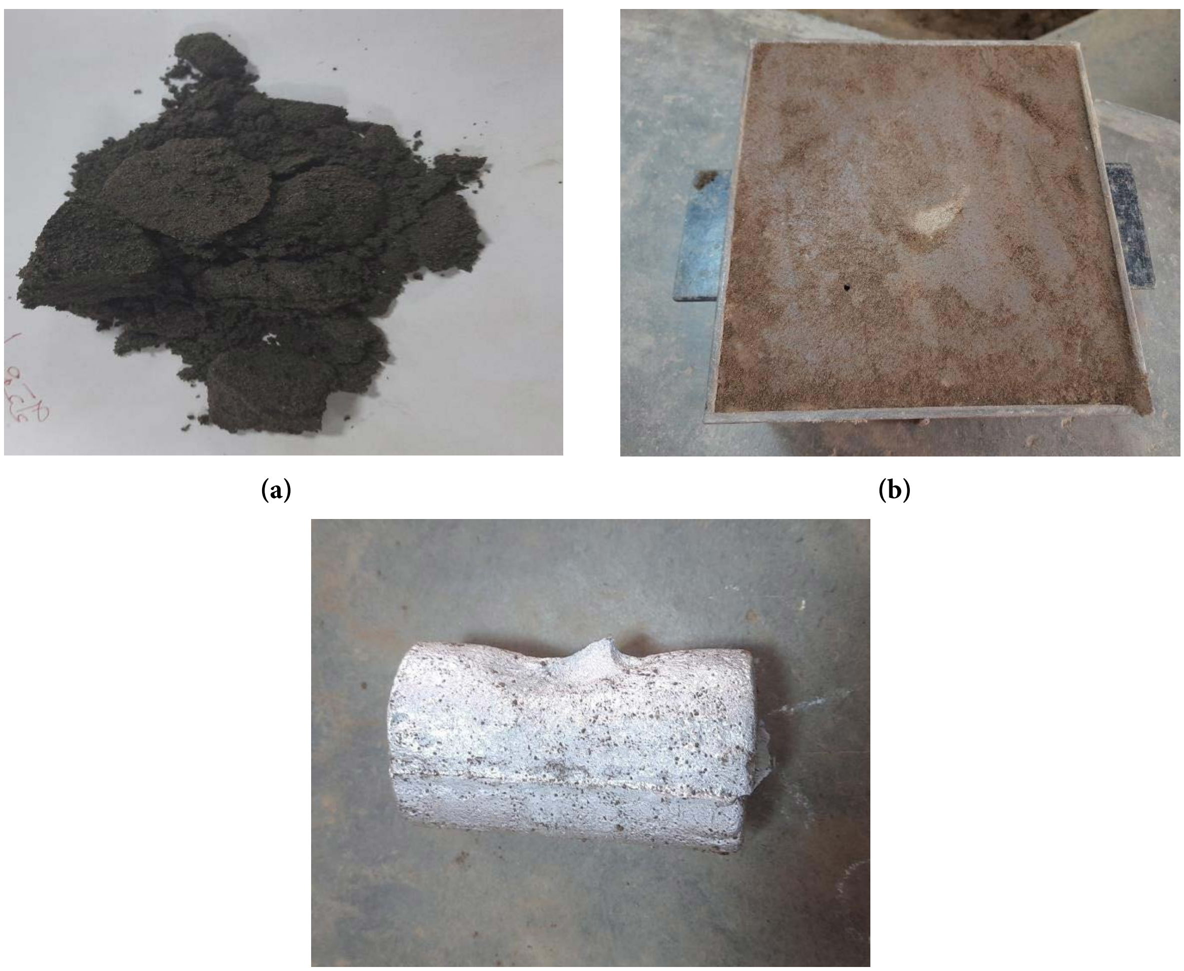


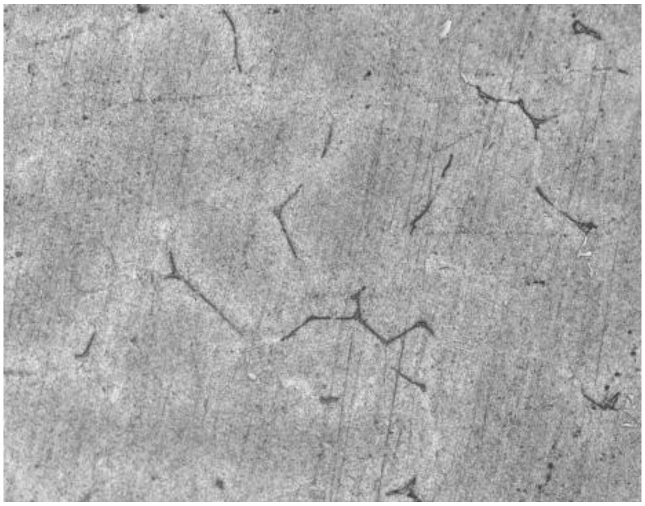
Figure 2. SEM and EDX of bio-waste and bagasse ash additives. **(a)** Bio-waste **(b)** Bagasse ash **(c)** EDX of bio-waste **(d)** EDX of bagasse ash.

sand/x%clay sand mould showed lower microhardness values. The yield and ultimate tensile strength of 6061Al alloy castings fabricated in different sand mould combinations is listed in Table 2. In case of 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould both yield and ultimate tensile strength values were found to increase as the weight percentage were increased from 5% to 15%. For all cases as the weight percentage of non-silica additives increased, both yield and ultimate tensile strength increased gradually. Overall 6061Al alloy casting developed in silica sand/x%bagasse ash sand mould showed highest strength values compared to others. The increase in microhardness, yield strength and ultimate tensile strength is attributed to small grain size. In general increment in strength in case of metals or alloys is mainly achieved via grain refinement. During melting and solidification process there are several routes which help in grain refinement and in that the type of mould used for casting process play an important role. Better escaping route for entrapped gas facilitated by the silica sand/x%bagasse ash sand mould and its high compression strength led to defect free and refined microstructure. This refined microstructure consisted of large number of small grains which means the number of grain boundaries was high. So as per the Hall-Petch relationship the metal or alloy will have high strength values when the number of small grains is large. This implies the presence of large number of grain boundaries inhibit the dislocation motion. Due to inhibited dislocation motion the alloy experiences work hardening and due to this 6061Al alloy possesses high strength (Lakshmikanthan *et al.*, 2019;

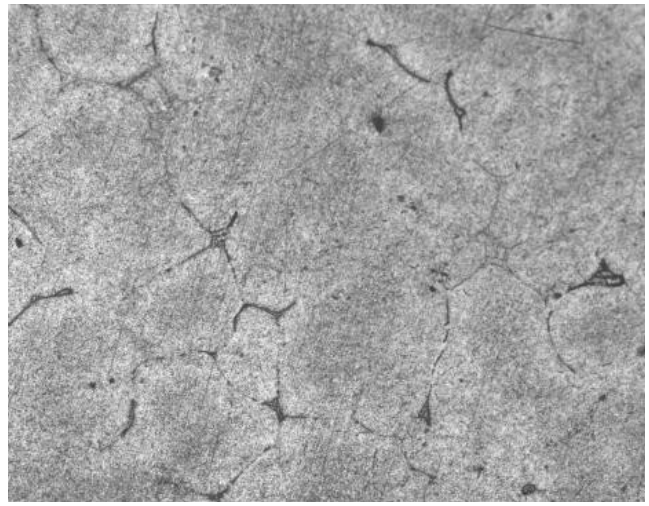


(a) **(b)** **(c)**

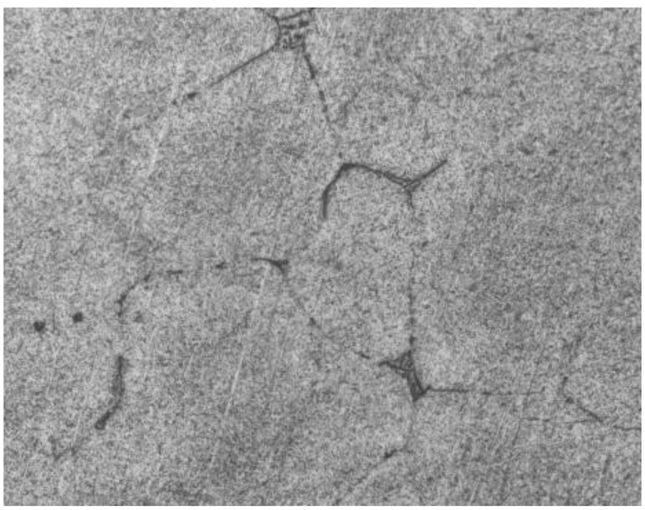
Figure 3. Photographs of mixed mould sand, mould and 6061Al casting. **(a)** Silica sand/15%bagasse ash **(b)** Sand mould prepared for pouring **(c)** 6061Al casting



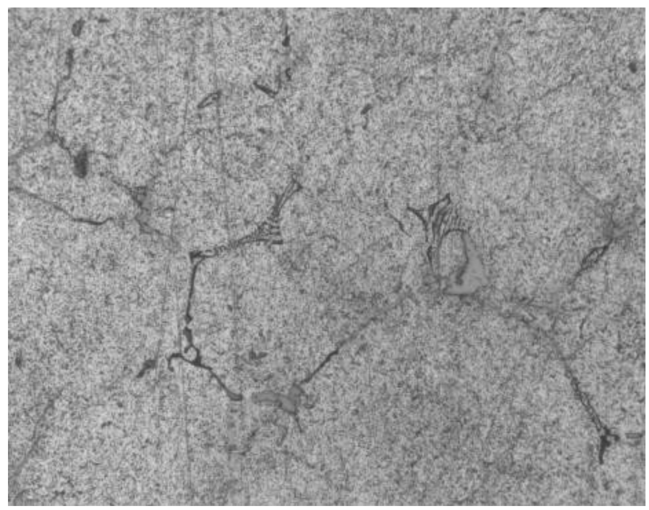
(a) 5%



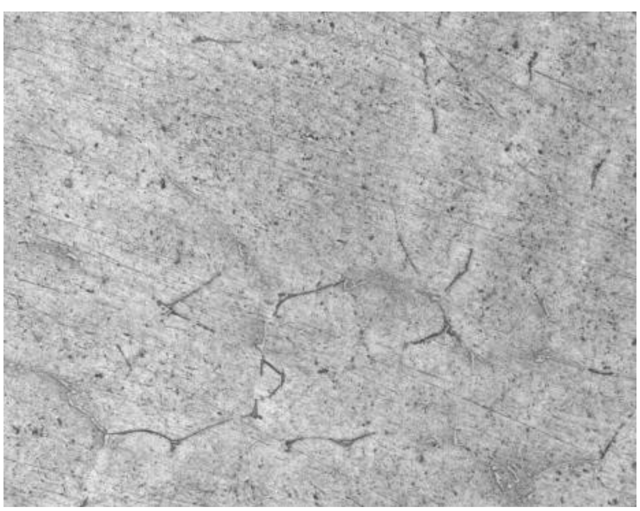
(b) 15%



(c) 5%

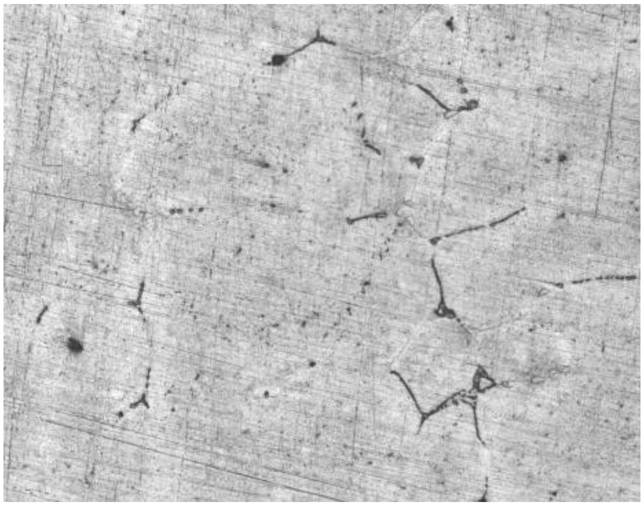


(d) 15%

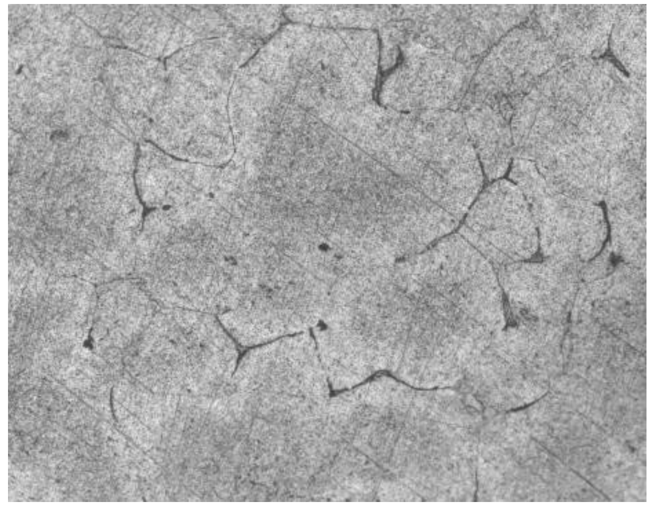


(e) 5%

(f) 15%



(g) 5%



(h) 15%

Figure 4. Optical micrographs of 6061Al alloy castings developed using **(a, b)** silica sand/x% clay sand mould **(c, d)** silica sand/x% bagasse ash sand mould **(e, f)** silica sand/x% nano-SiO2 sand mould **(g, h)** silica sand/x% bio-waste sand mould.

Iyengar *et al.*, 2021; Puneeth *et al.*, 2019; Lakshmikanthan *et al.*, 2020; Kumar *et al.*, 2016).

5. Results and Discussion

Figure 2 shows the SEM micrographs and EDX analysis of bio-waste and bagasse ash particles. The bio-waste particles seem to have amorphous structure with Ca, Al, Si, Mg, Ti and O as the main elements (Figures 2(a) and (c)). On the other hand the bagasse ash is having particulate morphology with Si, Ca, Fe, Al and O as the main elements. These elements correspond to SiO_2, Al_2O_3, Fe_2O_3 and CaO compounds and SiO_2 is the major constituent.

The size of both the additives was found to be in range of few microns to 50 μm. However large size particles are very few while the particles having size less than ~2 μm are large in numbers. Figure 3(a) shows silica sand/15%bagasse ash mixture and from photograph it is quite clear that mixing is quite uniform. Further the sand mould prepared for pouring molten 6061Al alloy is shown in Figure 3(b). The mould was prepared after subjecting a small sample for permeability, shear strength and compression strength.

Finally Figure 3(c) shows the photograph of cast 6061Al alloy which showed few inclusions on surface otherwise no other defects were visible. Figures 4 (a) to (h) shows the optical microstructure of 6061Al alloy fabricated in different sand moulds. For instance the micrographs shown in Figures 4(a) and (b) corresponds to 5% and 15% clay content incorporated sand moulds which showed decrease in grain size as the content of clay was increased. Similarly for all cases as there was increased from 5% and 15% the grain size of the 6061Al alloy was found to decrease gradually. The decrease in grain size is attributed to pouring of molten metal at high temperatures in the sand mould which contain optimum coarse-fine mixture of particles (Ajibola *et al.*, 2015).

6. Conclusions

In the present work an attempt is made to partial replacement of silica sand by adding additives like clay, bio-waste, bagasse ash and nano-SiO_2 in different weight percentages (5% – 15%). The effect of additives on sand mould and casting properties are studied and the conclusions drawn are given below:

- The silica sand/x%bagasse ash and silica sand/x%nano-SiO_2 sand moulds showed highest permeability number indicating better in facilitating the gases to escape from the mould. The silica sand/x%bagasse ash mould showed higher shear strength and compressive strength properties.
- The surface roughness of cast 6061Al alloy was found to decrease with the increase in additive content from 5% to 15%. Out of all, the 6061Al alloy castings developed in silica sand/x%bagasse ash sand mould showed lower surface roughness values.

- The mechanical properties like yield and ultimate tensile strength were found to increase with the increase in additive content from 5% to 15%. The 6061Al alloy castings developed in both silica sand/x%bagasse ash and silica sand/x%bio-waste sand moulds showed higher strength values.

From this work it is quite clear that the bagasse ash is better additive to silica sand in improving the sand mould and casting properties.

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