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The mechanical characteristics of 6063 aluminum alloy cast in a mixture of aluminum dross and silica sand as mold have been examined. The amount of dross in the green silica sand was varied in the range of 0–80% with bentonite as binder. In all, 40 samples were cast, and 8 of these were left in the as-cast condition for control while 32 were first homogenized at 470°C for 6 h and then rolled in a two-high mill at ambient temperature to 10% reduction in one pass. The rolled samples were solution heat treated at 515°C for 8 h followed by normalizing, annealing, and quench tempering, respectively. The samples were then simulated and tensile behavior coupled with the evaluation of microhardness and microstructures developed. The results obtained demonstrate significant improvement in mechanical properties from 50% to 80% dross in the mold. Tensile strength increased to 177 MPa and 15% elongation compared with conventional 6063-T5 aluminum alloy with 145 MPa tensile strength and 8% elongation. The improvement in mechanical properties by the quench-tempered samples can be attributed to the inducement of fine and coherent Mg_2Si crystals within the matrix. Furthermore, the overall analysis of the proportion of dross to the size of cast show that about 64% of dross generated can be utilized as mold material.

INTRODUCTION

Aluminum drosses both white and black are residues from primary and secondary aluminum production processing. White dross has a higher aluminum content as it is a waste from primary and secondary aluminum smelting, while the black dross with a lower metal content is generated during aluminum recycling. On remelting, refining, and casting of aluminum alloys, aluminum dross and nitrides of aluminum with entrapped metallic aluminum are generated at the surface of the molten metal. This emanates from its uncontrolled reaction with the furnace atmosphere at elevated temperatures.[1] Hence, recycling of aluminum dross is one of the most challenging tasks in die casting processes. This is because of the difficulty in separating the oxides from metallic aluminum even at a high temperature compared with other typical recovery processes, where the dross is normally melted at high temperatures in a furnace. However, at elevated temperatures, free metallic aluminum in the dross is susceptible to oxidation and often it is ignited and burned in the presence of air to emit toxic gases.[2] Hence, the dross as a byproduct does constitute not only a huge waste but also a veritable source of pollution to the environment.

Efforts at finding use for the various grades of aluminum dross are yielding fruitful results. It is established that the utilization of this material as filler in asphalt may improve stiffness and could also improve abrasion resistance and control microcracking.[3] This may be feasible because of the dross's intrinsic ability to promote intracrystal grains cohesion. Furthermore, the use of either white or black dross as filler at particle size $< 700\ \mu m$ has given rise to significant improvement in the strength characteristics of concrete and asphalt products.[4] Aluminum oxides produced from aluminum dross recycling also could be employed together with other alternative materials to produce premixes for clinker production. This can be achieved by using the type of materials that contribute essential components in cement's recipe, such as lime, silica, alumina, and iron oxide.

The study on the nonwaste aluminum dross recycling through alkaline leaching has led to the production of commercial aluminum hydroxide and a nonmetal product containing 80% alumina. The aluminum hydroxide was found to increase the molar ratio of aluminum to chlorine in the aluminum oxychloride solution used as coagulant in water purification. The alumina generated can also be used for refractory materials production.[5]

Aluminum drosses obtained from secondary smelting operations have been found to contain a mixture of aluminum alloy oxides and slag with recoverable aluminum contents between 12% and 18%.[6] However, a nonmetallic residue referred to as salt cake, which is generated and subsequently disposed in landfills, often contaminates underground water and surrounding vegetation. It is heart warming that salt-cake residue can now be processed through a process known as "dross waste upgrading." The process has demonstrated the ability to reduce energy consumption and the amount of dross material going into landfills.[7]

In response to increasing environmental health hazards occasioned by land filling with aluminum dross generated by aluminum smelting industries, the study on safe economic use of aluminum dross is imperative. In this article, the use of aluminum dross as a molding material for aluminum alloy castings and its effect on the mechanical properties are presented.

EXPERIMENTAL PROCEDURE

The molds used to cast samples of aluminum 6063 alloy were prepared from mixtures of green silica sand, bentonite, and aluminum dross. The amount of aluminum dross was varied in the range of 0–80%, while water and bentonite were 7% and 3%, respectively. The compositions of the molds mixes and the chemical composition of aluminum dross obtained from Aluminum Rolling Mills, Ota, Ogun State, Nigeria are presented in Tables I and II, respectively.

The aluminum 6063 alloy ingot (composition in Table III) was melted in a pit furnace from which cylindrical samples of length 150 mm and 15 mm diameter were produced. Prior to further processing, the cast samples were all homogenized at 470°C, soaked for 6 h, and air cooled.

One sample from each of the eight batches was designated as the control, while the remaining was rolled in a two-high mill at ambient temperature to 10% reduction. From the homogenized and rolled samples, standard tensile specimens were prepared in accordance to ASTM E8 and solution heat treated at 515°C for 8 h followed by annealing, normalizing, and quench tempering. The actual test was carried out using an Instron Electro Mechanical tester, model 3369 (Instron Corporation, Norwood, MA). The hardness of the samples was determined using the Avery hardness testing machine. The results obtained are illustrated in Figs. 1–3.

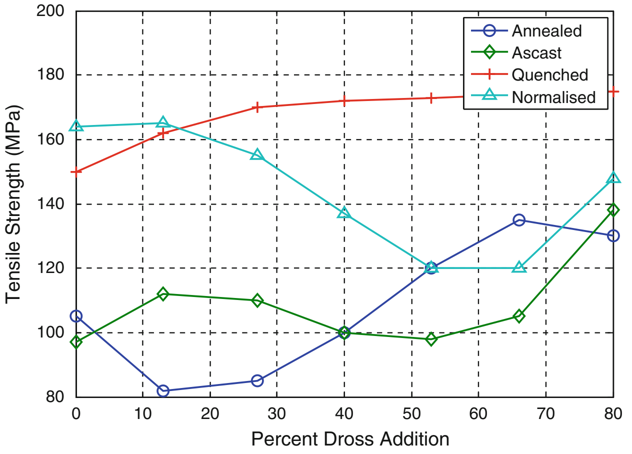

Fig. 1. Tensile strength against percent dross addition in green sand.

Table I. Molding Sand Mix Ratios

Batch Number	1	2	3	4	5	6	7	8
Green sand	50	75	20	100	–	–	–	50
Dross	50	25	80	–	50	25	80	–
Green sand + bentonite	–	–	–	–	50	75	20	50

Table II. Composition of Aluminum Dross

Constituents	Al	Al_2O_3	SiO_2	Fe_2O_3	CaO	K_2O	Na_2O	TiO_2	MgO
% Composition	9.8	71.1	2.6	2.4	0.1	0.8	2.1	1.0	10.1

Table III. Composition of Aluminum 6063 Alloy Ingot

Element	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
% Composition	0.479	0.024	0.076	0.053	0.481	0.068	0.004	0.005	98.81

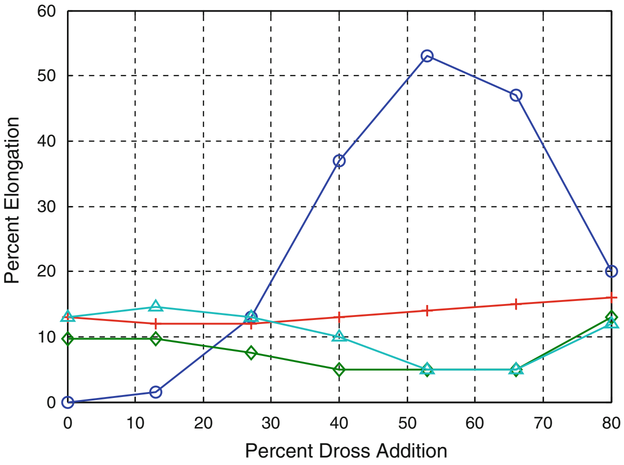

Fig. 2. Percent elongation against percent dross addition in green sand.

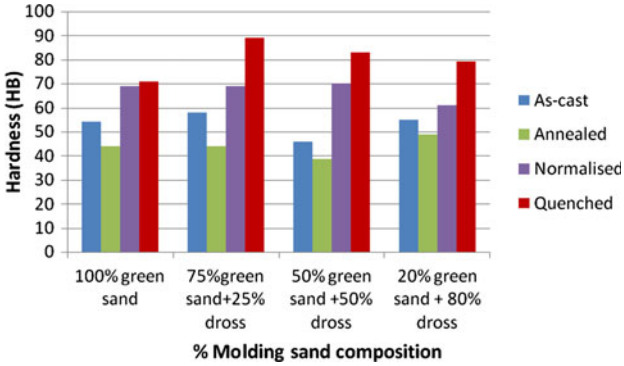

Fig. 3. Hardness variation against mold composition.

A microstructural test piece 20 mm thick was cut from both the as-cast and heat-treated specimens surfaces; the pieces were ground in succession with emery paper of grades 40, 32, 10, and 8. The ground surfaces were then polished with alumina paste and etched for 10 s in a solution containing 1 g NaOH pellets in 100 mL water. The specimens' microstructure was viewed using an optical metallurgical microscope at 100 times magnification, and their photomicrographs are presented in Figs. 4–7.

RESULTS AND DISCUSSION

Tensile Strength

In Fig. 1, the as-cast specimens demonstrate an initial rise in tensile strength from 98 MPa to 127 MPa as up to about 25% dross was added to the molding sand. After this, a steady decline in tensile strength from 127 MPa to 99 MPa was observed for 30% to 67% dross in the mold, which again increased to 138 MPa at 80% dross mold mixture.

The annealed test specimens demonstrated opposite behavior to that of the as-cast; the strength values are relatively lower at all dross contents in the mold. Although the normalized specimens exhibited higher strengths compared with both as-cast and annealed specimens, nevertheless, the specimens show a general decline in strength from 0% to about 70% dross content when the values rose from 120 MPa to 145 MPa. The responses of the as-cast (Fig. 4a–d), annealed Fig. 5a–d), and normalized (Fig. 6a–d) specimens stemmed from the structure developed in each specimen. The crystals are inhomogeneous and incoherent while the annealed shows coarse Mg_2Si precipitates. The strength of quench-tempered test specimens increased steadily from

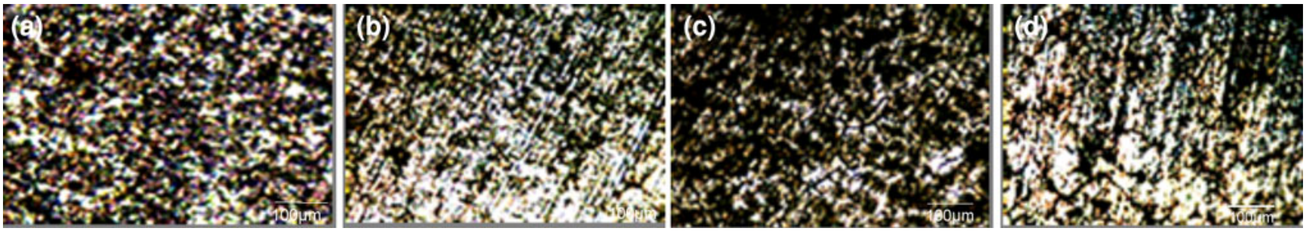

Fig. 4. Microstructures of as-cast samples: (a) 100% green sand, (b) 25% dross + 75% green sand, (c) 50% dross + 50% green sand, and (d) 80% dross + 20% green sand.

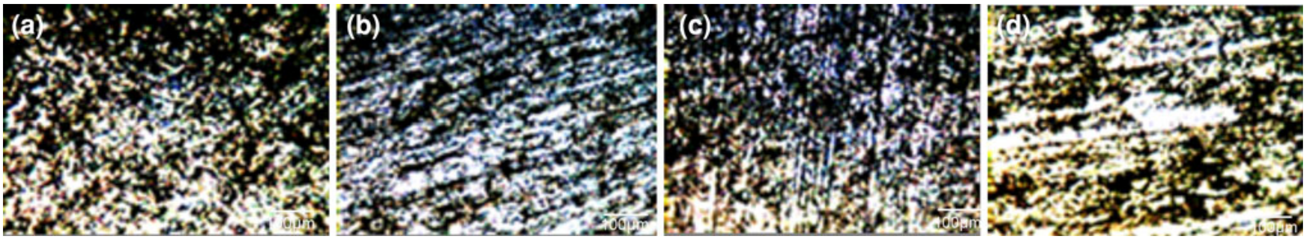

Fig. 5. Microstructures of annealed samples: (a) 100% green sand, (b) 25% dross + 75% green sand, (c) 50% dross + 50% green sand, and (d) 80% dross + 20% green sand.

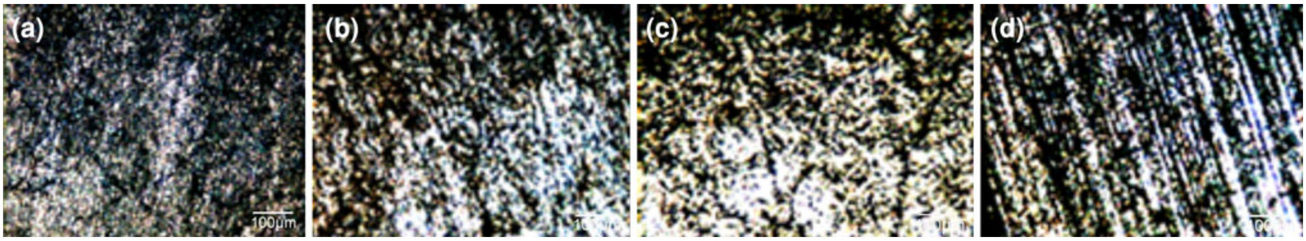

Fig. 6. Microstructures of normalized samples: (a) 100% green sand, (b) 25% dross + 75% green sand, (c) 50% dross + 50% green sand, and (d) 80% dross + 20% green sand.

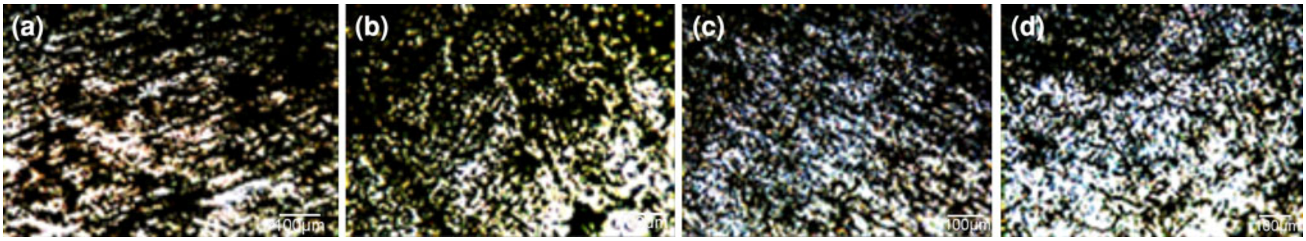

Fig. 7. Microstructures of quench-tempered specimens: (a) 100% green sand, (b) 25% dross + 75% green sand, (c) 50% dross + 50% green sand, and (d) 80% dross + 20% green sand.

150 MPa up to the peak, 178 MPa at 0% to 80% dross in the mold. It is observed that the rates of increase in strength at the lower level of dross addition were higher than at the higher levels. This is an indication that there is a progressive increase in the fineness and coherency of Mg_2Si crystals precipitated at the grain boundaries (Fig. 7a–d).

Ductility

The ductility of the as-cast specimens as shown in Fig. 2 is the least, 10–12% compared with the heat-treated specimens, 12–15% at all percent dross addition in the mold. On the other hand, the annealed specimens exhibited a rather superfluous elongation, 53% at about 50% dross proportion in the mold, but the elongation dropped to 20% at 80% dross in the mold.

However, the ductility response of the quench-tempered specimens shows a steady rise in percent elongation and peaked at 15% for the mold containing 80% dross. The preponderance of fine crystals of AlFeSi dispersed homogeneously throughout the matrix must have been responsible for this behavior. It is established that the precipitation of crystals of ductile AlFeSi and Al-Cu intermetallics enhances elongation (Fig. 5a–d).

Microhardness

The level of microhardness induced in the as-cast and annealed specimens was relatively low and generally inconsistent. For example, at 0% and 50% dross in the mold mixture, the hardness values are 52 HB and 46 HB, respectively, while 44 HB and 38 HB were recorded for the annealed. This can be attributed to the extremely low volume fraction of the Mg_2Si reinforcing crystals coupled with their inhomogeneous dispersion in the matrix. It is observed that the water-quenched and tempered specimens demonstrated the highest microhardness values, 89 HB, 82 HB, and 80 HB at 25%, 50%, and 80% dross addition in the mold. The increased presence of fine Mg_2Si crystals in the matrix over AlFeSi crystals would appear to have been responsible for this behavior.

Microstructure

Figures 4–7 show the microstructure of test specimens at varying dross proportions in the mold coupled with the different heat treatment administered on the cast alloy specimens.

The microstructures of the as-cast specimens are shown in Fig. 4a through d as mold composition varied from 0% to 80% dross. There was a general subdued precipitation of second-phase crystals. Rather, the matrix is dominated by α-Al in which the few precipitates present are subsumed.

Figure 5a–d shows the annealed specimens microstructures in which the AlFeSi precipitated are the stable crystals as opposed to Mg_2Si precipitates. The few AlFeSi crystals present are observed to have been coarsened due to a rather slow cooling rate of the specimens in the furnace. The variation observed in the extent of grain coarsening arose from the different amount of dross in the mold. It is established that the ease with which heat is able to escape from a mold during solidification of cast depends on the mold's permeability, which is a function of the volume of pores available after ramming of the mold. Permeability is also influenced by the amount of binder and any other secondary mold material(s) used.

The normalized test specimens' microstructures are presented in Fig. 6a–d. At varying dross proportion in the mold coupled with solution heat treatment that culminated in open-air cooling, the Mg_2Si crystals precipitated within the α-Al matrix became coarse. However, the precipitates are coherent and homogeneous.

Figure 7a–d shows the microstructure of the quench-tempered test specimens in which fine precipitates of Mg_2Si crystals are quite substantial and evenly dispersed in the matrix.

The overall observed behavior of the test specimens is greatly influenced by the dross chemical composition (Table II).The dross contains refractory compounds such as Al_2O_3 and MgO, which have the capacity to absorb heat more quickly from the molten alloy than the green sand, giving rise to fine crystals in cast samples. Consequently, the addition of aluminum dross to green sand for molding and its subsequent heat treatment promotes the precipitation of fine coherent crystals of Mg_2Si that correspondingly increased tensile strength, ductility, and micro-hardness properties.

OTHER RELEVANT DROSS IN MOLD ISSUES

Estimated Annual Utilization of Dross in Mold

About 4.2 metric tons of dross is generated daily from 32 metric tons of aluminum ingots cast at a typical aluminum processing company in Nigeria. This translates to about 840 metric tons of dross generated annually by the company. Given the projected effective usage of 50–80% dross as mold material in this study, an analysis of the ratio of the quantity of dross to the size of aluminum cast is 0.64. With this, it is estimated that about 537.6 metric tons of dross can be utilized annually as mold material in a foundry shop, leaving the balance of 302.4 metric tons for landfills. Another benefit of the process is that dross as a component in mold sand can be recycled as many times just as the conventional silica sand is normally recycled.

Deterioration of Properties on the Addition of Dross Above 80%

The presence of alumina and magnesium oxide in dross serves the purposes of gradual replacement of silica in molding sand and as binder, respectively. Given that a good mold must possess adequate strength and refractoriness, there is always a limit to which alumina and magnesia can effectively substitute for the intrinsic properties of silica sand grains. Hence, the strength and refractoriness of the mold produced with dross content above 80% is weak. This gave rise to erosion of the mold cavity during casting with impurities being carried along into the melt, which resulted in microsegregations at grain boundaries of the cast. It is established in material structure integrity analysis that microsegregation often significantly reduces crystal grains cohesion. This must have been responsible for property impairment at higher dross addition observed in this study. By this result, it can be concluded that 80% is the upper limit for dross addition in mold meant for casting 6063 aluminum alloys.

Any Risk Involved in the Use of Dross as a Mold Material?

This study has not established any risk or issue associated with the use of aluminum dross as a mold material. It is pertinent to state further that the environmental challenges peculiar to aluminum dross disposal have to do with leaching of metallic aluminum into rivers and soil, thereby polluting the ecosystem. This is because at elevated temperatures, the nitride component of aluminum dross oxidizes emitting toxic gases that pollute the air. These conditions do not subsist in the use of dross as foundry material for casting aluminum alloys as the processes are carried out below 700°C. Furthermore, it should be noted that the particles of aluminum dross are held together by a binder (bentonite), which prevents the particles from being blown by air into the atmosphere. During molding, it is the usual practice for molders to use a nose mask, thereby preventing any inhalation that could cause health problems. This practice is also encouraged when using aluminum dross.

CONCLUSION

The study has shown that aluminum dross addition to green silica sand as mold material enhances the cast mechanical properties. However, it follows from the results that the use of dross above 50% may impair mold permeability, which will necessitate solution heat treatment of the cast for improved mechanical characteristics. Hence, the improvement in mechanical properties of test specimens must have been aided by heat treatment in particular, quench tempering of the cast alloy. Compared to conventional 6063-TS aluminum, application of aluminum dross in the range 50–80% gave rise to improved tensile strength in the quench-tempered cast from 145 MPa to 177 MPa, modest ductility 8–15%, and enhanced microhardness from 46 HB to 82 HB. This newfound use for aluminum dross is capable of promoting its industrial utilization, thereby reducing considerably the peculiar health hazards occasioned by usage as landfill material. It will also give rise to a significant reduction in the cost of mold material for aluminum alloy castings.

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