

## EFFECTIVE RECYCLING OF CAST ALUMINIUM ALLOYS FOR SMALL FOUNDRIES

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### ABSTRACT

A method of effective recycling of aluminium castings suitable for small foundries was investigated. Automotive cast aluminium scrap obtained from various scrap vendors was sorted into groups of similar components, namely; pistons, cylinder heads and housings (gearbox and rear-axle housings). This sorting method was adopted with the hypothesis that the resulting alloys could be closely equivalent to the commercial alloys that were originally used to make the components. The remainder of the scrap was grouped as miscellaneous scrap and contained various parts such as alternator covers, exhaust manifolds, oil sumps and other assorted scrap.

As hypothesised, the chemistry of the resulting alloys were found to be consistently equivalent to the commercial alloys commonly used to cast the various components that were melted. For example, the alloy chemistry of secondary alloys from piston scrap was consistently equivalent to commercial piston alloys such as AC8B and LM26. Furthermore, alloys from cylinder head scrap were equivalent to commercial alloys such as 319, LM27 and AC2B. On the other hand, the alloy chemistry from unsorted scrap was not found to be consistent nor equivalent to a specific group of commercial alloys except for the 319 and 380.0 workhorse alloys. These results are discussed against the possibility of reusing the alloys in casting components similar to those that they were recycled from, in addition to other possible applications.

**Key words:** Cast aluminium, aluminium recycling, Al-Si alloys



## 1.0 INTRODUCTION

Cast aluminium alloys are widely used in automotive and aerospace industries. They are used in automotive pistons, wheels and cylinder heads. As a key trend, manufacturers are changing the material for engine blocks from cast iron to aluminium resulting in significant weight reduction. Aluminium castings are also being used in other automobiles parts, such as intake manifolds, transmission housings, valve bodies, channel plates, rear axle and differential housings, drive shafts, brackets, brake master cylinders, suspension components and steering components (Cole and Sherman, 1995). With the escalation of fuel costs and environmental concerns, aluminium is being preferred for production of other components of ground transportation vehicles. Cast aluminium alloys are also used in a wide variety of other engineering applications. As an example, they are used in oil tanks and pans, machine tool parts, marine hardware, pump parts, valve bodies, bridge railing parts, rudder control supports, landing flap mountings, aircraft wheels, fuselage fittings and fuel tank elbows for airplane and compressor bodies. The list is by no means exhaustive.

Cast Al-Si alloys are some of the most widely used alloys because of the flexibility provided by the high silicon content and its contribution to castability. Most of these alloys also respond well to heat treatment after casting to obtain the required combination of ductility and strength. The most common of these alloys belong to the hypoeutectic group in which the silicon content is below the eutectic at around 11.7% Si. Eutectic Al-Si alloys have exceptional fluidity and feedability and are therefore preferred for complex castings. Hypereutectic alloys have silicon contents above the eutectic and are commonly used in applications that require high wear resistance and low thermal expansion. The automobile components listed are cast mainly from Al-Si based alloys (Hatch, 1984; Jorstad, 1984). However, Al-Mg cast alloys are preferred for marine applications because of their improved corrosion resistance. Al-Cu based cast alloys are used in some aircraft components that require higher strength although they are difficult to cast because of their tendency to hot tear.

Cast aluminium alloy products are widely used in Kenya. After their service life is over, some of the scrap is exported while the rest is usually ploughed back for recycling by the Kenyan foundry shops for use in casting other products. It is common practice to find foundry shops in Kenya melting scrap obtained from different components together without regard to their varied chemical compositions and impurities. This melting practice is likely to be a major setback to the successful recycling of aluminium alloys because facilities for on-line chemical composition analyses are scarce locally. The problem is complicated further by the large number of different alloys being used to make various components. Furthermore, cast aluminium parts from different countries entering the scrap stream have not been exposed to the same processing methodologies. As an example, antimony is often used to control the eutectic silicon structure in Europe (especially France) and Japan, but it acts as an impurity in the strontium-modified alloy castings produced in North America and Australia (Taylor, 1995). In addition, different alloys are often



used to produce similar components depending on the product model (e.g., vehicle model) and the manufacturer's preferences.

Sorting techniques such as laser-induced breakdown spectroscopy, x-ray fluorescence and neutron activation analysis have been used with various degrees of commercial success (Green, 2007). These techniques are particularly suitable for segregating between cast and wrought aluminium alloys and even between different wrought alloys. However, these technologies involve heavy capital investment and can only be available in large scale foundries and in the premises of secondary aluminium producers for economic reasons. Even with the availability of these tools, cast scrap is normally not segregated further because it would be overly expensive and time consuming for large scale recycling. The melt chemistry is therefore corrected during remelting to standard secondary alloys using on-line spectrometers and element additives. This is a challenge for small foundries that may not afford an on-line chemical correction facility.

Most Kenyan foundry shops segregate cast aluminium from wrought aluminium usually by visual inspection of the scrap parts based on knowledge of their processing route. The cast scrap is usually not segregated further and alloy correction is seldom done because of lack of on-line chemical analysis facilities. This leads to a high degree of uncertainty in the expected properties of the products cast from these alloys due to uncertainty in the resulting alloy chemistry. The situation is worsened further by the fact that the alloy chemistry of the resulting secondary alloys is difficult to determine, even after the castings have been poured because of lack of reliable and economical local laboratories for chemical composition analyses.

A suitable cast scrap recycling method is needed for such small foundries to ensure reliable castings. It is, therefore, necessary to carry out studies on the recycling of cast aluminium scrap so as to develop better practices that will contribute to the improvement of the quality of aluminium castings produced under the circumstances described. It is speculated that further sorting of cast scrap by melting similar components in isolation is likely to result in repeatable alloy chemistries. As stated previously, different alloys are often used to produce similar automotive components depending on the vehicle model and the preferences of the manufacturer. However, the performance requirements of similar components are expected to vary within a limited range. This implies that the alloys to be used are also likely to have properties that do not vary significantly. The probability of using alloys whose chemical compositions vary within a limited range is therefore high. This provides the basis for sorting the scrap component-wise because it is hypothesised that the alloy chemistry of the resulting secondary alloys will be equivalent to the chemistries of the standard alloys from which the scrap components were originally made. On the other hand, it is also hypothesized that if cast aluminium alloy scrap components were to be cast together without further sorting, the resulting alloys are likely to have significantly varied chemical compositions. This is because different components have different performance

requirements and although some alloys may be able to meet the requirements of



two or more components, it is likely that most will not. Therefore several different alloys, whose chemical compositions vary significantly, will be used for the different components. The alloy chemistry of the resulting alloys are therefore likely to vary significantly depending on the components recycled and the alloys they were originally made from.

This paper reports the findings of a preliminary investigation that was done to test this hypothesis. The objectives of the study were to determine the typical chemical compositions of recycled alloys obtained from different cast aluminium scrap components and analyse variations from sample to sample. The chemistries of the resulting alloys are compared with those of equivalent commercial alloys. They are also discussed against the possibility of reusing the alloys in casting components similar to those that they were recycled from, in addition to other possible applications.

## **2.0 METHODOLOGY**

### **2.1 Scrap Sorting and Classification**

Pools of approximately 100 kg of assorted cast aluminium scrap were purchased from six different vendors selected randomly. This was done to determine the common scrap components available in the Kenyan market (at least within Nairobi). The scrap was then sorted component-wise. The scrap components identified were; pistons, cylinder heads, gearbox housings, rear axle housings, alternator covers, exhaust manifolds, oil sumps and other assorted scrap items. The assorted items are those that could be identified to be cast aluminium by comparative visual inspection of their design and surface, but were too few in number.

The scrap components above are mostly motor vehicle parts, usually from cars, light trucks (including public transport vehicles) and heavy trucks. The most common of these components were found to be pistons, cylinder heads, gearbox housings and, to a lesser extent, rear axle housings. Pistons and cylinder heads were classified individually as pistons and cylinder head groups; while gearbox and rear axle housings were grouped together as housings. The rest were not as common and were collectively lumped together under miscellaneous scrap. These groups were coded as follows: P for pistons, C for cylinder heads, H for housings (gearbox and rear axle housings) and M for miscellaneous scrap. The miscellaneous scrap included the remaining scrap items (i.e. alternator covers, exhaust manifolds, oil sumps and assorted scrap)

To determine typical chemical compositions of the scrap groups, it was found necessary to melt at least three samples randomly picked from each group. These were coded as follows:

- P1, P2 and P3 for pistons.
- C1, C2, C3 and C4 for cylinder heads.
- H1, H2, H3, H4 and H5 for Housings.
- M1, M2, M3 and M4 for miscellaneous scrap.

### **2.2 Melting and Pouring**



Scrap samples of 25 kg each were charged into a diesel fired crucible furnace and melted under a cover flux. At melt temperatures of around 750°C, the dross was skimmed off and the melt degassed with degassing tablets for hydrogen removal. For each secondary scrap alloy, small cast samples were poured and quenched in un-preheated mild steel moulds for chemical analysis. The chemical composition of the samples was then determined using an OES-5500 optical emission spark spectrometer. The metal was then poured into green sand and permanent moulds at pouring temperatures of between 730°C and 750°C.

### 3.0 RESULTS AND DISCUSSION

Table 1 shows the chemical compositions of the secondary alloys, P1 to P3, obtained from recycled pistons and those of equivalent alloys of different designations popularly used to make pistons as given in some references (Hatch, 1984; Kehler, 1980; Brown, 1999 Barnes and Lades, 2002. Note that compositions are in wt % and single values represent maximum limits throughout the paper. The table also includes chemistries of three secondary alloys (PS1, PS2 and PS3) obtained from recycled pistons that are reported in the literature (Haque and Maleque, (1998) Haque and Sharif, 2001; Mose *et al*, 2010). It is observed that the alloy chemistries of the secondary alloys obtained in this study from recycled pistons are well within the normal specifications for pistons. It is noteworthy that the alloy chemistries are fairly consistent although the Si content is slightly low (just about the specified low limit for alloys AC8B and LM26). It is not clear why this is the case, but the secondary alloys PS1, PS2 and PS3 which were all obtained from piston scrap have fairly high Si levels as shown in Table 1. Alloys obtained from piston scrap are therefore expected to have Si levels of about 8 to 12%Si. The Ni contents are also slightly higher than the specification limit for most piston alloys except for Aluminium Association's 336.0 alloy as shown in Table 1. This could possibly be due to additional Ni coming from the cast in Ni ring carrier usually placed at the top ring groove region to improve wear resistance (Barnes and Lades, 2002).

Pistons are usually cast from near eutectic Al-Si cast alloys with high levels of Cu, Mg and Ni. Eutectic alloys are preferred because they have excellent fluidity and feedability due to their near zero solidification range. The high Si also imparts high dimensional stability, scuff resistance, wear resistance and lower thermal expansion to the alloy. These are key functional requirements for pistons which must be maintained over a wide range of operating temperatures (Barnes and Lades, 2002). In the early 1990s, indirect injection light vehicle diesel engines operated at 300°C at the combustion bowl edge with maximum cylinder pressures approaching 13 MPa.



Table: The chemical composition of recycled and equivalent commercial piston alloys

Alloy	Si	C <sub>n</sub>	Mg <sub>2</sub>	Fe	Mn	Ni	Zn	Cr	Pb	Sn	Ti	Al
P1	7.88	1.61	.47	.90	.08	1.83	11	.02	.06	1.0	1.0	Bal
P2	8.56	2.05	.70	.61	.07	1.73	.08	.02	.04	.06	.06	Bal
P3	8.02	2.31	.84	.84	.26	1.73	1.0	.02	.05	.07	.05	Bal
AC8E	8.5-10.5	2.0-4.0	.5-1.5	1	.5	1-1.1	.5	1	1	.2	1	Bal
AC8K <sup>a</sup>	11-13	8-13	.7-1.3	.8	1.5	8-15	1.5	1	.05	.05	.2	Bal
LM13 <sup>b</sup>	10-12	.7-1.5	8-1.5	1	.5	1.5	.5	-	.1	.1	.2	Bal
LM26 <sup>c</sup>	8.5-10.5	2-4	.5-1.5	1.2	.5	1	1	-	.2	.1	.2	Bal
3320 <sup>d</sup>	8-10	2-4	.5-1.5	1.3	.5	.5	1	-	-	-	.25	Bal
3360 <sup>e</sup>	12	1	1	1.2	-	2.5	.35	-	-	-	-	Bal
3390 <sup>f</sup>	12	2.25	1	1.2	-	1	1	-	-	-	-	Bal
PM120 <sup>g</sup>	12	1	1	0.7	-	1	-	-	-	-	0.1	Bal
P41 <sup>h</sup>	12.2	.85	.75	.86	.11	2.5	1.0	-	-	1.2	-	Bal
P81 <sup>i</sup>	10.1	.41	1.2	1.6	.55	1.1	.05	-	-	.37	-	Bal
P83 <sup>j</sup>	10.6	1.36	.78	1.1	.08	1.1	.09	-	.01	.02	.06	Bal

<sup>a</sup>Kehler (1980). <sup>b</sup>Brown 1999). <sup>c</sup>Hatch (1984). <sup>d</sup>Barnes and Lades (2002). <sup>e</sup>Haque and Maleque (1998). <sup>f</sup>Haque and Sharif (2001). <sup>g</sup>Mose et al. (2010).



In the early 2000, these had gone up to 400°C and 17.5 MPa, respectively due to increased performance. Future high performance direct injection engines will operate at over 400°C and pressures above 20 MPa (Barnes and Lades, 2002). Furthermore, new pistons of reduced weight are being developed with some designs advocating for reduced crevice volume (the volume between the cylinder wall surface, the piston outside wall and the top of the piston ring) by moving the top piston ring closer to the top of the piston. This design reduces hydrocarbon emissions by minimising unburned fuel trapped in the crevice volume. Piston alloys are therefore required to have high mechanical and thermal fatigue strength at between 200°C and 400°C after prolonged exposure to these temperatures. They should also have a low coefficient of thermal expansion, high wear resistance and high thermal stability without excessive thermal growth at high temperature.

These high temperature strength requirements for pistons are achieved by increased Cu, Mg and Ni contents in the alloy. Copper contents of between 1 to 4 % are usually specified and forms the  $\theta'$ -Al<sub>2</sub>Cu and S'-Al<sub>2</sub>CuMg strengthening phases by combining with Al and Mg. However, at piston service temperatures, these phases rapidly coarsen and form the non-coherent  $\theta$ -Al<sub>2</sub>Cu and S-Al<sub>2</sub>CuMg phases with accompanying loss of strength and dimensional stability due to thermal growth. It has been suggested that these strengthening phases can be stabilised by controlling the Cu/Mg ratio of about 4 to 15 with Mg not less than 0.5% (Lee and Chen, 2005). Furthermore, the same authors assert that a Si/Mg ratio of about 14 to 18 also ensures sufficient Mg<sub>2</sub>Si minor strengthening precipitates. However, the addition of Ni at levels between 0.5 to 2.5% forms various strengthening Ni-containing phases such as Al<sub>3</sub>Ni and Al<sub>3</sub>Ni<sub>2</sub> that are exceptionally stable at high temperature which help stabilise the Cu phases (Lee and Chen, 2005). Increasing both Cu and Ni results in thermally stable AlCuNi strengthening intermetallics (Barnes and Lades, 2002). Nickel also forms FeNiAl phases that are also stable at high temperature and provide further strengthening.

Iron levels of between 0.1 to 2% have also been specified for these alloys (Tahinata *et al.*, 2008). Iron forms various stable intermetallic compounds that improve high temperature strength. Recent investigations are looking at increasing the performance of piston alloys by further increasing the Cu and Ni contents and increasing the Si level slightly above the eutectic; although there are concerns about reductions in castability (Barnes and Lades, 2002; Tahinata *et al.*, 2008). These elements combine amongst themselves and with others like Fe to form a high concentration of different types of intermetallic compounds which lead to improved elevated temperature strength (Edwards *et al.*, 2002; Chen *et al.*, 2006; Cho *et al.*, 2003). Small additions of titanium, vanadium and zirconium have also been suggested to further improve high temperature strength (Lee and Chen, 2005; Edwards *et al.*, 2002; Cho *et al.*, 2003; Jayamathy and Vasanth, 2006). These elements form compounds of the Al<sub>3</sub>X type (X=Ti, V, Zr) having L1<sub>2</sub> structure which are stable and impart high temperature strength and creep properties. These particles also act as grain refiners for  $\alpha$ -Al primary dendrites. For hypoeutectic to eutectic alloys, it is recommended that Sr be added to modify the eutectic Si from



coarse acicular plates to fine fibrous Si particles. However, care should be exercised as Sr tends to increase porosity. Antimony can also be used for this purpose without the increase in porosity although it only refines the eutectic Si to fine lamellar structures and needs careful handling because it is toxic. For hypereutectic compositions, small amounts of P should be added to refine the primary Si particles. Large eutectic and primary Si particles tend to act as early fatigue crack initiators and thus reduce the fatigue performance of the alloy.

It is important to note that some pistons are cast from Al-Cu alloys such as 240, 242 and 243 (Hatch, 1984). It is difficult to identify and isolate such pistons from the mainly Al-Si piston scrap and the resultant cast alloy may have high Cu contents when such pistons are present in appreciable amounts. However, these alloys are less frequently used and would therefore not present a serious challenge to the recycling process. The secondary alloys obtained from pistons can therefore be successfully reused to cast pistons without significant loss in performance. However, as mentioned above, minor additions of eutectic Si modifiers such as strontium and antimony or primary Si refiners such as phosphorus depending on the Si level are necessary to improve the fatigue properties.

Table 2 gives the chemical composition of alloys, C1 to C4, obtained from recycled cylinder heads together with the chemistries of equivalent commercial alloys. These are commonly used to make cylinder heads alongside a variety of other applications. The table also includes a secondary alloy, CS, recently obtained from recycled cylinder heads in a separate study (Mose *et al.*, 2008b). It is important to note that in addition to the commercial alloys in Table 2, cylinder heads are cast from a variety of other Al-Si alloys with varying chemistries including 354 (AlSi9Cu1.6Mg), A356 (AlSi7Mg) and even A380 (AlSi9Cu3) and W328 (AlSi9Cu1) (Garat and Laslaz, 2007; Feikus, 1998; Gundlach *et al.*, 1994; Engler-Pintor Jr. *et al.* 2004; Fischersworing-Bunk, *et al.*, 2007; Emadi *et al.*, 2006; Koch *et al.*, 1999). It is thus less likely to expect repeatable equivalent chemistries in alloys recycled from them. This is evident in the recycled alloys in which the Cu content varies from a low of 1.22 to a high of 3.09 %. The high Si content of 8.79 % reported for CS compared to the low values for C1 to C4 underscores this point. However the alloys obtained are still individually fairly equivalent to at least one of the commercial alloys listed. For instance, C1 and C4 are equivalent to alloy LM27 while C2 and C3 are equivalent to the remaining commercial alloys. However, apart from the variations in Si and Cu levels which should be expected, the rest of the elements are largely consistent with the general specifications for cylinder head alloys.

Cylinder heads are subjected to severe thermal fatigue in the combustion chamber. This results from thermal cycling between ambient and about 300°C that cause repeated constrained thermal expansion and contraction. The material suitable for this application must therefore have a low thermal expansion coefficient, high tensile and compression strength, high ductility and a high creep resistance at ambient and elevated temperature. Furthermore, the alloy should have a high thermal conductivity, high corrosion resistance and must remain dimensionally stable during service. The alloy must also have high castability and machinability. This





is a challenging combination of properties to achieve as some of the requirements are in conflict and an optimum balance is required. For instance, Cu and Mg are used to increase room and high temperature strength and creep but may result in a deterioration in ductility and could lead to thermal growth problems (Feikus, 1998). Furthermore, Cu also increases the tendency to form porosity and hot tears (Feikus, 1998; Caceres *et al.*, 1999; Gruzleski and Closset, 1990). That explains the use of absolutely opposed alloys such as the elevated temperature soft and ductile A356



Table 2: The chemical composition of recycled and equivalent commercial cylinder head alloys

Alloy	Si	Cu	Mn	Pb	Mg	Ni	Zn	Cr	P	S	Ti	Al
C1	5.82	1.74	0.01	0.38	0.22	0.01	0.17	0.01	0.10	0.08	0.02	Bal
C2	5.86	2.93	0.01	0.21	0.25	0.04	0.18	0.01	0.01	0.01	0.01	Bal
C3	5.41	3.09	0.04	0.71	0.29	0.04	0.27	0.01	0.12	0.08	0.01	Bal
C4	1.01	1.21	0.08	0.43	0.38	0.02	0.11	0.01	0.07	0.05	0.05	Bal
AC2A <sup>a</sup>	4-6	3-4.5	2.5	8	5.5	3	5.5	1.5	1.5	0.5	2	Bal
AC2B <sup>a</sup>	5-7	2-4	5	1	5	3.5	1	2	2	1	2	Bal
TM4 <sup>a</sup>	4-6	2-4	1.5	8	2-1	3	5	-	1	1	2	Bal
TM21 <sup>a</sup>	5-7	3-5	1-3	1	2-1	3	2	-	2	1	2	Bal
TM22 <sup>a</sup>	4-6	2.8-	0.5	1	2-1	1.5	1.5	-	1	0.5	2	Bal
TM27 <sup>a</sup>	1-8	1.5-	3	8	2-1	3	1	-	2	1	2	Bal
319 <sup>a</sup>	5.5-	2.2-4	0.5-	4-1	1-5	-	3	-	-	-	-	Bal
C8 <sup>a</sup>	8.79	1.38	1.7	4.1	2.4	0.2	0.8	0.1	0.1	0.1	0.1	Bal

<sup>a</sup>Kehler (1980). <sup>b</sup>Brown (1999). <sup>c</sup>Hatch (1984). <sup>d</sup>Mose et al. (2009).



Addition of about 0.5 % Cu to A356 has been found to yield a compromise alloy (Garat and Laslaz, 2007; Feikus, 1998; Engler-Pintor Jr. *et al.* 2004). It has also been shown that addition of small amounts of transition elements Ti, Zr and V improves the creep resistance of the A356+0.5%Cu alloy without loss in ductility (Garat and Laslaz, 2007). The same study also showed that reducing the Mg and Fe levels in 319 while adding the transition elements in small amounts leads to exceptionally high ductility in addition to improved creep resistance. The removal of Mg also allows high solution temperatures to be used during heat treatment and reduces the quench rate sensitivity of the alloy, thus reducing residual stresses. The alloys obtained in this study have low Mg levels although the Fe levels are a bit high. They are therefore expected to have low ductility but with improved strength and creep resistance especially after heat treatment to the thermally stabilized T7 condition.

A low thermal expansion coefficient and good casting properties are obtained at high Si contents. However, the heat conductivity is improved by low contents of Si and Mg and ductility can also be improved by modification of the eutectic Si (Feikus, 1998). It is instructive that the specified Si levels for cylinder head alloys are not as high as those of piston alloys so as to optimise ductility and heat conductivity.

Table 3 gives the alloy chemistries of alloys obtained from gearbox and rear axle housings together with approximately equivalent commercial alloys which are also usually used to cast these parts.



Table 3: The chemical composition of recycled and equivalent commercial gearbox and rear axle housing alloys

Alloy	Si	Cu	Mn	Pb	Mg	Ni	Zn	Cr	Fe	Sn	Ti	Al
B1	714	3.30	0.08	0.82	0.14	0.14	1.14	0.03	0.13	0.14	0.05	Bal
B2	709	3.02	0.04	0.83	0.19	0.10	0.44	0.03	0.09	0.08	0.04	Bal
B3	728	3.21	0.04	0.84	0.21	0.12	0.84	0.03	0.12	0.09	0.04	Bal
B4	813	3.49	0.07	0.90	0.24	0.15	0.75	0.05	0.13	0.18	0.04	Bal
B5	843	3.07	0.04	0.90	0.23	0.11	0.68	0.03	0.15	0.18	0.04	Bal
ADC10	75-95	2.4	3	9	5	35	1	-	-	3	-	Bal
LM24 <sup>a</sup>	75-95	3.4	3	13	5	5	3	-	3	2	2	Bal
319 <sup>b</sup>	55-8	2.2-4	0.5-1	4-1	1-5	-	3	-	-	-	-	Bal
380.0 <sup>c</sup>	75-95	3.4	1	2	5	5	3	-	-	35	-	Bal

<sup>a</sup>Kehler (1980). <sup>b</sup>Brown 1999). <sup>c</sup>Hatch (1984). <sup>d</sup>Emadi et al. (2006). <sup>e</sup>Makhlouf et al. (1995).



These parts are usually cast using high pressure diecasting in which a high Fe level is specified to mitigate die soldering. As expected, the Fe level of the secondary alloys is high and in line with diecast alloys such as ADC10, LM24 and 380. The 319 type alloy is a secondary alloy that is not usually diecast, but it is equivalent to the alloys obtained here because of its wide specification limits and diverse applications. The 319 type of alloys are increasingly being used for engine crankcases, engine blocks, cylinder heads, gearbox and rear axle housings, manifolds, engine mounts (i.e., powertrain applications) and other miscellaneous engine parts. It is, therefore, not surprising that most of the scrap samples are approximately equivalent to this group of alloys. This is further underscored by a recent study by Njuguna (2007) who recycled unsorted automobile scrap and obtained 319 type alloys.

Finally, Table 4 shows the compositions of the alloys obtained from the miscellaneous scrap mentioned earlier as well as the approximately equivalent alloys. It is not expected that these alloys would be equivalent to a particular group of alloys. However, they are still seen to be equivalent to some commercial alloys which are commonly used for general engineering parts such as the 319 and 380 type alloys.



Table 4: The chemical composition of recycled miscellaneous scrap and approximately equivalent commercial alloys

Alloy	Si	C	Mg	Pb	Mn	Bi	Zn	Cr	Pb	Sn	Ti	Al
MF1	6.75	3.54	0.13	0.71	0.20	0.23	1.32	0.02	0.15	0.18	0.04	Bal
MF2	7.14	2.04	0.15	0.72	0.22	0.29	0.62	0.02	0.12	0.12	0.05	Bal
MF3	5.62	1.90	0.13	0.67	0.24	0.13	1.20	0.03	0.10	0.18	0.06	Bal
MF4	7.34	2.35	0.18	0.90	0.19	0.59	0.48	0.02	0.09	0.09	0.05	Bal
AC21B	5.7	2.4	5	1	5	35	1	2	2	1	2	Bal
ADG10	7.5-9.5	2.4	3	9	5	35	1	-	-	3	-	Bal
319	5.58	2.4	0.5-1	4-1	1-3	-	3	-	-	-	-	Bal



The analyses of the chemistry of the secondary alloys shows that the sorting method discussed is quite effective and can result in alloys whose chemistry can be predicted easily based on the components recycled and prior knowledge of alloys originally used to make them. Furthermore, the secondary alloys can be reused to cast components similar to those they were recycled from without significant loss of performance. This is confirmed by their as-cast mechanical properties which compare fairly well with some of their commercial equivalents as shown in Table 5. Perhaps the easiest to predict is the alloy chemistry of secondary alloys recycled from cast aluminium wheels. Cast aluminium wheels are almost exclusively made from the 356/357 type alloys and their equivalent designations like the LM25 and AC4H. Work in one of the author's laboratory has consistently shown that recycled wheels result in alloys equivalent to 356 or 357 alloys. If high ductility is a necessary requirement and service temperatures are low, then it may be advisable to use alloys recycled from cast aluminium wheels.



Table 5: As-cast mechanical properties of sand and permanent mould cast secondary alloys investigated and those of some of the equivalent commercial alloys as reported in the literature.<sup>1</sup>

Alloy	Green sand casting			Permanent mould casting		
	UTS (MPa)	El (%)	BHN	UTS (MPa)	El (%)	BHN
P1	128	1.7	65-85	123-160	1.5-2.3	90-95
P2	120-160	1.4-2.2	86-90	146-166	2.0-2.4	90-98
P3	146-170	2.0-2.4	75-86	135-196	1.9-3.3	88-99
P8-1	120	1.6	62	175	2.4	78
P8-2	125	2.0	65	-	-	-
P8-3	-	-	-	138-142	2.0-2.8	78
C1	119-136	1.4-1.7	62-74	125-170	1.5-2.0	69-76
C2	120	1.5	69-76	168-190	2.0-2.3	72-80
C3	122	1.5	72-76	133-145	1.7-1.9	76-80
C4	138-160	1.7-2.1	64-72	167-198	1.9	74-81
LM4	150	2.0	70	200	3.0	80
LM21	180	1.0	85	200	2.0	90
LM27	190	2.0	75	180	3.0	80
319	186	2.0	70	234	2.5	85
H1	136	2.0	76-80	165-185	2.2-2.4	85-90
H2	118-124	1.5-1.7	62-72	164-192	2.1-2.6	90
H3	106	0.7	80	157-179	2.1-2.4	87-90
H4	130-162	1.9-2.5	74-81	168-203	2.0-2.9	87-90
H5	105-135	0.9-2.0	68-76	134-171	2.0-2.4	87-90
LM24	-	-	-	200	2.0	85
M1	105-130	0.8-1.8	7-80	157-167	2.0-2.5	85-87
M2	-	-	-	157-157	2.0-2.2	80-83
M3	-	-	-	159-172	2.3-2.5	87-90
M4	128-162	1.4-2.7	74-78	160-192	2.4-3.0	80-84

<sup>1</sup>The mechanical properties of some of the equivalent commercial alloys are reported in the following references: Haque and Maleque (1998); Haque and Sharif (2001); Mose et al. (2010); Brown (1999); Hatch (1984).





Aluminium castings are generally used in the heat treated condition and it was therefore difficult to find as-cast mechanical properties for most of the commercial alloys. Pistons are mostly used in the T5 overaged condition while cylinder heads are used in T7 temper. A recent study by one of the authors reported tensile strengths as high as 309 MPa for a permanent mould recycled piston alloy heat treated to the T6 condition. In the same study, the CS alloy shown in Table 2 yielded a maximum T6 tensile strength of 274 MPa. Aluminium die castings are usually used in the as-cast condition because heat treating causes expansion of gas porosity previously flattened under high pressure leading to an undesirable blistered surface.

#### 4.0 CONCLUSION

A method of recycling aluminium castings that is suitable for small foundries was investigated. The object of the study was to determine the typical chemical compositions of recycled alloys obtained from different cast aluminium scrap components, analyse variations from sample to sample and establish equivalence with commercial alloys commonly used to cast the components. It was hypothesized that an effective method of recycling cast aluminium alloys to obtain consistent alloy chemistries is to sort and melt similar scrap components separately. This hypothesis was tested by melting scrap from pistons, cylinder heads and gearbox housings separately. Unsorted scrap items were also melted.

As hypothesised, the chemistries of the resulting alloys were found to be consistently equivalent to the commercial alloys commonly used to cast the various components that were melted. For example, the alloy chemistry of secondary alloys from piston scrap was consistently equivalent to commercial piston alloys such as AC8B and LM26. On the other hand, the alloy chemistry from unsorted scrap was not found to be consistent nor equivalent to a specific group of commercial alloys except for the 319 and 380.0 workhorse alloys. It is concluded that melting similar scrap components can result in alloys that can be reused to cast the same components without significant degradation of mechanical performance.

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