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RECYCLING OF ALUMINUM A380 MACHINING CHIPS

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Abstract

Aluminum and its alloys have experienced significant increases in their usage in the automotive industry for the past few decades. Large quantity of aluminum is being produced everyday with huge waste such as dross and chips. Due to environmental and cost issues, production of aluminum via recycling is increasingly becoming a must for further expansion. However, technologies for aluminum recycling are far from perfection, in particular for machining chips. In this work, machining chips of aluminum alloy A380 were collected from computer numerical control (CNC) machines and then cleaned. The cleaned chips were thermally recovered with two fluoride-containing fluxes and one fluoride-free flux. The recovery rate of the recycled metal was determined based on weight measurements. The results of tensile testing, microstructure analysis and chemical composition evaluation indicate that the quality of the recovered metal is comparable to die-cast A380.

Introduction

In the past two decades, aluminum alloys as a light weight material have been increasingly used in the automotive industry. Worldwide average aluminum content was 7.8% of the average worldwide light vehicles curb weight of 3,183 pounds in 2009. North America (NA) has the highest aluminum penetration at 8.6% of North America curb weight in the world. The usage of aluminum in North American automobiles has gone from 45kg (101 lbs.) in the 1970s to 150 kg (326 lbs.) in 2009, and will top 170 kg (376 lbs.) per vehicle by 2020. Among the 150 kg aluminum usage in each vehicle, almost 35% of automotive aluminum components were manufactured by conventional high pressure die-casting (C-HPDC) processes [1]. When C-HPDC components are manufactured, considerable amount of aluminum waste in the form of scrap, dross, and machining chips is produced as byproducts. The casting scrap is easily returned to melting, whereby most of the metal is recovered and re-utilized in production processes. The recovery of aluminum from dross can be achieved at a recovery rate of around 80% by mixing dross and chips with certain types of flux [2-6]. During the recycling of chips and dross, however, a lot of metal is lost as a result of oxidation, and the costs of labor and energy as well as the expenditure on environmental protection increase the general cost of the process. The chips as a by-product not only bring huge waste, but also could produce pollution to the environment. Also, due to high market demand for cost saving on die castings, the recovery of Al chips becomes critical for die casters. However, recovery rates of the chips are often unknown to die casting shops since most chips are presently recycled externally and aluminum content in the chips depends on the practice of molten metal processing.

According to Gronostajski J.[7], in the process of melting aluminum and aluminum alloy chips, on average 10% of the metal is burnt and about 10% is lost because dross formed by mixing molten aluminum and slag were removed from the surface on the ladle. And add by 8% loss of casting scraps, 72% aluminum would be recycled after casting. Thus the anticipated recovery rate is around 72%.
In this study, the chips collected directly from CNC machines were recycled with flux. The recovery rate of the recycled metal was determined based on weight measurements. To ensure the quality of the recycled aluminum, the chemistry of the recovered aluminum was analyzed. The cleanliness of the recycled metal was assessed based on microstructural analysis. The tensile properties of the recovered aluminum cast in an ingot mold were evaluated.

Experimental Procedures

Materials

Machining chips of aluminum alloy 380 shown in Figure 1 were the raw material to be recycled, of which chemical composition is listed in Table 1.

Figure 1 Machining chips of aluminum alloy 380.

Table 1 Chemical Compositions of Aluminum Alloy A380 [8]

Alloy	Element (in wt. %)			
A380	Si	Cu	Zn	Fe
	7.5-9.5	3.0-4.0	3.0 max	1.3 max
	Ni	Mg	Sn	Mn
	0.5 max	0.1 max	0.35 max	0.5 max

Cleaning

For safety and health considerations, wet machining chips should be cleaned before thermal recycling. There are several cleaning methods such as cleaning with solvent, thermal method and hot press. In this study, cleaning with water and solvent was applied, and their cleaning effect was concluded by the observation of the reduction in smoke emission during the heating stage of the thermal recycling process. The clean processes included rinsing wet chips with water at room temperature, and soaking them in plastic buckets with acetone for 6 hours, ladling them onto aluminum foils, and dry them in a fume hood for 12 hours.

Refining

300g of cleaned chips were loaded into a clay-graphite crucible inside an electric resistance furnace, the crucible was heated to 500°C for 20 minutes of preheating to remove moisture, and then refining flux was added into the crucible to cover the chips. Three different kinds of fluxes made by Basic Resources Inc. were selected for the purpose of comparison. They were Al-clean 101 [9], Al-clean 113 [10] and Al-clean 116 [11]. Two of them, Al-clean 101 and Al-clean 116 were fluoride-containing flux, and Al-clean 113 was fluoride-free flux. 1:1 of chips/flux weight ratio was employed. The crucible with chips and flux was held at 500°C for 20 minutes.

Melting and casting

After chips and flux were preheated, the temperature of the furnace was increased to 800°C for 60 minutes to 90 minutes. The slag floating on top of liquid aluminum was scooped out. After cleaning the slag, the recovered liquid aluminum alloy was poured at 720°C into an ingot mold and cast as a plate. The solidified aluminum plate was quenched in tap water. Three typical experiments on cleaned chips were conducted following Table 2. Here, each trial of 22 experiments was carried out based on previous trial. Here, No.11, 16 and 18 were selected for their high recovery rate. And to reach the ideal recovery rate, flux types, chips/flux ratio and holding time were selected as the influencing factors during these experiments.

Table 2 experimental records of refining and melting processes

No.	Chips (g)	Flux type	Chips/flux ratio	Hold time (min)	
				Heating	Melting
11	300	116	1 : 1	15	60
16	300	113	1 : 1	20	75
18	300	101	1 : 1	20	60

Determination of recovery rate

Chips were weighed prior to refining experiments, and the recovered aluminum alloy was weighed after the experiments. The recovery rate of the chips was determined based on the following expression:

$$\text{Recovery Rate (\%)} = (\text{Weight of recovered Al}) / (\text{Chips Weight})$$

Quality Assessment of Recycled Al Alloy

Density measurement

Following the measurement of specimen weight in the air and distilled water, the actual density (D_a) of each sample with the dimensions of 10x10x10 mm was determined using the Archimedes' principle [12].

$$D_a = W_a D_w / (W_a - W_w)$$

Where W_a and W_w are the weight of the specimen in the air and in the water, respectively, and D_w is the density of water.

Tensile testing

The mechanical properties of the recycled aluminum were evaluated by tensile testing, which was performed at room temperature on a MTS criterion Tensile Test Machine (Model 43) equipped with a data acquisition system. Following ASTM B557 - 14[13], 3 chosen flat tensile specimens (25 mm in gage length, 6 mm in width, and 3 mm in thickness) were machined from each recycled aluminum plate and 3 tensile tests were carried out for each flux type.. The tensile properties, including ultimate tensile strength (UTS), 0.2% yield strength (YS), and elongation to failure (E_f) were recorded during the tests.

Microstructure analysis

The microstructure of the recycled alloy characterized by a Buehler optical image analyzer 2002 system was used to determine the primary characteristics of the specimens prepared by the standard metallographic procedure. The detailed features of the microstructure were analyzed using a FEI Quanta 200 FEG scanning electron microscope (SEM).

Chemical analysis

The chemical composition of the recovered alloy was analyzed by an optical emission spectrometer (ARL 4460 metal analyzer).

Results and Discussion

Recovery Rate

Table 3 lists the recovery rates of three typical Al chips samples from the CNC machines and cleaned with acetone. For the purpose of comparison, the data listed in Table 3 were also plotted in Figure 2. It can be seen that the recovery rates of the chips are around 90%, three kinds of fluxes have similar effect on aluminum recovery rate.

Table 3 Recovery rates of recycled aluminum chips

No.	Cleaned chips weight (g)	Weight of recovered Al (g)	Recovery rate: (wt. %)
11	300	268	89.3%
16	300	265	88.3%
18	300	271	90.3%

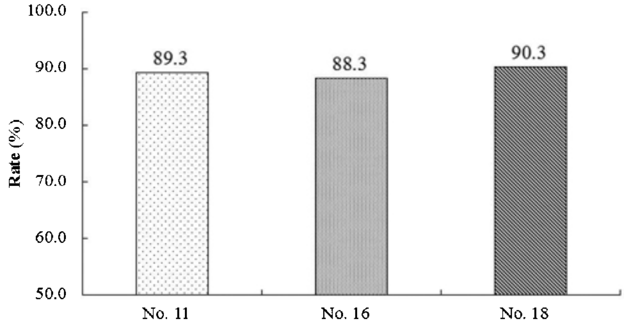

Figure 3 Recovery rates of twenty-two recycling experiments.

Density Measurement

The density measurements of the recovered aluminum are given in Table 4. Those recycled aluminum have an average density of 2.7567 g/cm^3. which was slightly lower than that of the die-cast A380 alloy [14].
Generally, the relatively low density is due possibly to the fact that the recovered aluminum which was cast in an ingot mold under open atmosphere may be less dense than die cast alloy 380 under an applied pressure with low porosity. Compared to No.16, which had a holding time of 75minutes during melting process, the density of No.11 and No.18 were slightly lower because of the entrapment of porosity and impurities. It suggested that the extended holding time during refining enhanced the elimination of oxides and impurities from chips by the reaction between the flux and chips.

Table 4 Density measurement of recycled aluminum

No.	11	16	18	Alloy A380 (Die-cast)[14]
Density (g/cm3)	2.7572	2.7917	2.7213	2.7981

Tensile properties

According to Table 5, die casting aluminum-alloy A380 has the tensile strength of 182.18 MPa; here the recycled ones reached 202.71 MPa, and also the other two have UTS values higher than the die cast one. It may be because the water quenching right after casting the recycled alloy led to an increase in the UTS.

The yield strength of the die cast A380 is 136.02 MPa. But, the yield strength of the recycled alloys was lower than 100 MPa. The reduction in yield strength should be likely attributed to the fact that the recovered alloys entrapped porosity and impurities due to incomplete refinement. This observation suggested that the secondary refining needs to be applied the recycled alloys for further cleaning. .

Table 5 Tensile properties of the recovered alloy and A380

No.	11	16	18	Alloy A380 (Die-cast)[14]
UTS (MPa)	187.23	202.71	192.87	182.18
YS (MPa)	92.3	91.12	91.36	136.02
E_f(%)	2.79	4.37	3.10	1.11

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Microstructure analysis

Figures 3 to 5 show the microstructures of the aluminum alloys recovered from chips. It is seen from Figure 3 that the recovered alloy had some black dots, which were porosity and oxides. But the content of porosity and oxide inclusions ratio was relatively low. It is evident that the microstructure of the ingot mold-cast recovered aluminum alloy contained α ($Al_{15}Fe_3Si_2$) phase and β (Al_5FeSi) phase, Si phase, $CuAl_2$. The phase observation indicates that the recovered aluminum alloy possessed the same types of phases as those present in the die cast A380 given in reference 14.

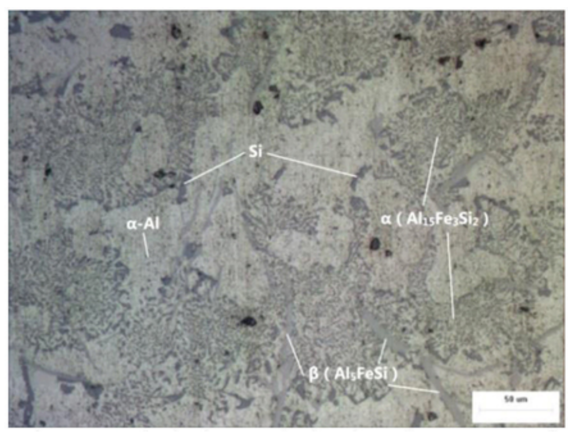

Figure 3 Optical micrograph showing microstructure of the recycled alloy.

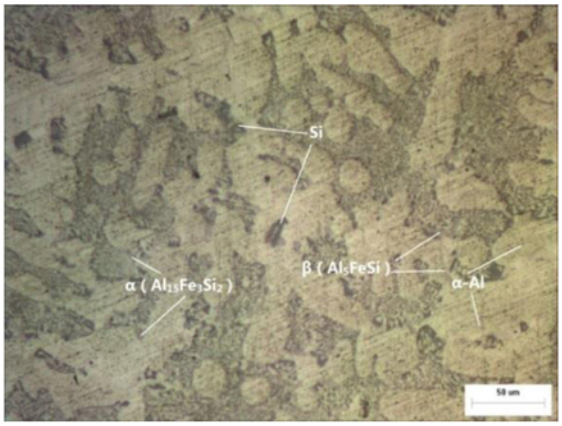

Figure 4 Optical micrograph showing microstructure of the recycled alloy.

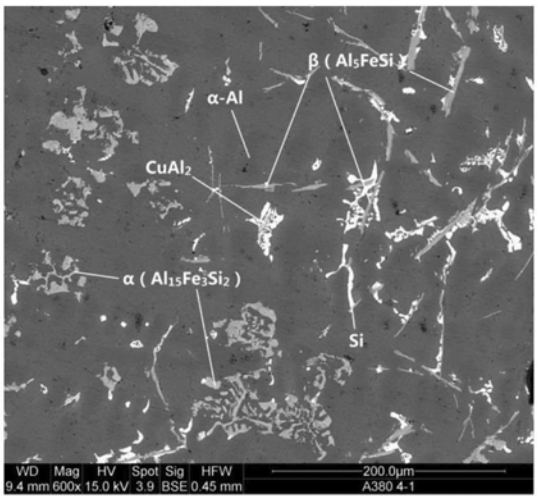

Figure 5 SEM micrograph showing microstructure of the recycled alloy

Chemical analysis

Though chemical analysis was carried on 3 pieces of recycled plates from experiment No. 11, 16, 18, they exhibited similar results. Table 6 exhibits the chemical composition of recovered aluminum plates. It is seen the chemical composition for most elements of recovered metal was similar to die-cast A380 aluminum referring to Table 1 mentioned above.

Compared to Figure 1, concentration of each element were still within the range. However, silicon concentration was in a high level within the range 7.5-9.5 while magnesium had a relative low concentration. This is possibly because silicon is more stable in elevated temperature compared to magnesium; magnesium would be more likely oxidized than silicon at the temperature.

Table 6 Chemical composition of the recovered aluminum alloys

No.	Element (in wt. %)			
	Si	Cu	Zn	Fe
11	9.353	3.315	2.043	1.016
16	9.400	3.454	2.054	0.976
18	9.414	3.332	2.298	1.000
	Ni	Mg	Sn	Mn
11	0.077	0.006	0.019	0.219
16	0.081	0.009	0.020	0.208
18	0.077	0.006	0.020	0.220

Conclusions

Conclusions were drawn based on recycling experiments in this study:

1. Acetone is a good agent to remove oil emulsion presented on the surface of aluminum machining chip.
2. Cleaning fluxes 101, 113 and 116 had similar influence on recovery rates, but considering environmental concerns, Al-clean 113, a fluoride-free flux, was suggested.
3. The recovery rate of aluminum alloy chips A380 reached as high as 90.3%.
4. The mechanical properties of the recovered aluminum were as good as those of the die-cast A380 aluminum alloy. The microstructure of the recovered aluminum alloys also contained the primary α-Al, Si phase, $CuAl_2$, Fe containing inter-metallic phases, which are almost the same as those present in the die cast A380. Despite of high concentration of silicon and low concentration of magnesium, the recovered aluminum alloy had an acceptable chemical composition.

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References

1. 2015 North American Light Vehicle Aluminum Content Study, Ducker Worldwide LLC, http://www.drivealuminum.org/research-resources/PDF/Research/2014/2014-ducker-report, June, 2014.
2. H. Y. Ghorab, M. Rizk, A. Matter, and A. A. Salama, "Characterization and Recycling of Aluminum Slag", Polymer-Plastics Technology and Engineering, Vol. 43, No. 6, 2004, 1663-1673
3. J.Y. Hwang, X. Huang, and Z. Xu, "Recovery of Metals from Aluminum Dross and Saltcake", Journal of Minerals & Materials Characterization & Engineering, Vol. 5, No. 1, 2006, 47-62.
4. B. Lucheva, T.S. Tsonev, R. Petkov, "Non-Waste Aluminum Dross Recycling", Journal of Chemical

Technology and Metallurgy, Vol. 40, No. 4, 2005, 335-338.
5. Shuping Wang, Henry Hu Yeou-li Chu, and Patrick Cheng, "Dross Recovery of Aluminum Alloy 380", 2008 NADCA Transactions, 2008, T08-013
6. H, Puga, J. Barbosa, D. Soares, "Recycling of aluminium swarf by direct incorporation in aluminium melts", J. Materials Processing Technology, 2009, 209 (11), 5195-5203.
7. Gronostajski J, Matuszak A. The recycling of metals by plastic deformation: an example of recycling of aluminium and its alloys chips, J. Journal of Materials Processing Technology, 1999, 92: 35-4
8. "Standard Specification for Aluminum-Alloy Die Castings" ASTM B85/B85M-14, Vol.02.02, www.astm.org., October, 2014.
9. Material safety data sheet, Al-clean 101 flux, Basic Resources, Inc, 2010, Knoxville, TN, USA.
10. Material safety data sheet, Al-clean 113 flux, Basic Resources, Inc, 2010, Knoxville, TN, USA.
11. Material safety data sheet, Al-clean 116 flux, Basic Resources, Inc, 2010, Knoxville, TN, USA.
12. "Standard Test Method for Density of High-Modulus Fibers" D3800M − 11, Vol.15.03,www.astm.org., Aug, 2011.
13. "Standard Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-alloy products", B557M-14, ASTM Standards, ASTM, Vol.02.02, May, 2014.
14. H. Hu, Y. Wang, Y. Chu, P. Cheng, and A. T. Alpas, Solution Heat Treatment of Vacuum High Pressure Die Cast Aluminum Alloy A380, NADCA Transactions, 2005, 22-33.