การตรวจสอบและปรับปรุงสมบัติของอะลูมิเนียมผสมรีไซเคิลโดยการเติมซิลิคอนและแมกนีเซียม

Investigation and improvement of the properties of recycled aluminum alloy by adding Si and Mg

สุนิสา คำสุข[1*], จันทร์ฑา นาควชิรตระกูล[1] และ ณัฐพล ชมแสง[2]
Sunisa Khamsuk[1*], Chantra Nakvachiratrakul[1] and Natthaphol Chomsaeng[2]

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บทคัดย่อ

การศึกษานี้กระป๋องเครื่องดื่มอะลูมิเนียมที่ใช้แล้วถูกนำกลับมารีไซเคิล องค์ประกอบทางเคมีของแท่งอะลูมิเนียมผสมที่ได้จากการรีไซเคิลกระป๋องเครื่องดื่มอะลูมิเนียมที่ใช้แล้วถูกทำการวิเคราะห์ด้วยเครื่องอิมิสชันสเปกโทรมิเตอร์ แท่งอะลูมิเนียมผสมที่ได้จากการรีไซเคิลถูกนำกลับมาหลอมอีกครั้งที่อุณหภูมิ 750 องศาเซลเซียส จากนั้นเติมผงซิลิคอนในปริมาณร้อยละ 0.25 และร้อยละ 0.5 และผงแมกนีเซียมในปริมาณร้อยละ 1.5 และร้อยละ 3 เพื่อปรับปรุงสมบัติเชิงกลของอะลูมิเนียมผสม โครงสร้างจุลภาคและสมบัติเชิงกลของแท่งอะลูมิเนียมผสมรีไซเคิลและอะลูมิเนียมผสมรีไซเคิลผสมแมกนีเซียมและซิลิคอนที่ปริมาณส่วนผสมซิลิคอนและแมกนีเซียมแตกต่างกันถูกทำการวิเคราะห์ด้วยกล้องจุลทรรศน์แบบใช้แสง กล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด เครื่องทดสอบความแข็งและเครื่องทดสอบอเนกประสงค์ตามลำดับ ผลการวิจัยพบว่าโครงสร้างจุลภาคของอะลูมิเนียมผสมรีไซเคิลประกอบด้วยเฟสสารละลายของแข็งอะลูมิเนียมผสมแมกนีเซียมและแมงกานีสและตะกอนเฟสที่ 2 จำนวน 4 เฟส คือ $Al_{19}(Fe_3SiMn)$, $Al_{33}(Fe_3SiMn)$, $Al_{11}(Fe_2Mn)$ และ $Al_{19}(Mg_2Si)$ ความแข็งและความแข็งแรงดึงของอะลูมิเนียมผสมรีไซเคิลเพิ่มขึ้นเมื่อเติมผงซิลิคอนและแมกนีเซียม เมื่อเพิ่มปริมาณผงแมกนีเซียมจากร้อยละ 1.5 เป็นร้อยละ 3 ปริมาณตะกอนเฟสที่ 2 $Al_{19}(Mg_2Si)$ เพิ่มขึ้น ผลการศึกษานี้บงชี้ว่าการเติมซิลิคอนและแมกนีเซียมสามารถปรับเปลี่ยนโครงสร้างจุลภาคและปรับปรุงสมบัติเชิงกลของอะลูมิเนียมผสมรีไซเคิลได้

คำสำคัญ: กระป๋องเครื่องดื่มอะลูมิเนียม อะลูมิเนียมผสมรีไซเคิล อะลูมิเนียมผสมแมกนีเซียมและซิลิคอน โครงสร้างจุลภาค สมบัติเชิงกล

Abstract

In this study, used aluminum beverage cans were recycled and chemical composition of an aluminum alloy ingot obtained from the recycled cans was examined by emission spectroscopy. The ingots were remelted at 750 °C, and then 0.25 wt.% Si, 0.5 wt.% Si, 1.5 wt.% Mg and 3 wt.% Mg powders were added to improve the mechanical properties of the alloy. The microstructure and mechanical properties of the as-cast recycled aluminum alloy and recycled Al-Mg-Si alloy at different Si and Mg contents were investigated via optical microscopy (LOM), scanning electron microscopy (SEM), hardness tester, and universal testing machine (UTM). The results revealed that the microstructure of the recycled aluminum alloy ingot consisted of Al-Mg-Mn solid solution and four different secondary phases: $Al_{19}(Fe_3SiMn)$, $Al_{33}(Fe_3SiMn)$, $Al_{11}(Fe_2Mn)$, and $Al_{19}(Mg_2Si)$ phase. The hardness and tensile strength of the recycled

[1] ภาควิชาวิศวกรรมอุตสาหการ คณะวิศวกรรมศาสตร์ มหาวิทยาลัยบูรพา ตำบลแสนสุข อำเภอเมือง จังหวัดชลบุรี 20131
[2] ภาควิชาวิศวกรรมวัสดุขั้นสูง คณะวิศวกรรมศาสตร์ มหาวิทยาลัยบูรพา ตำบลแสนสุข อำเภอเมือง จังหวัดชลบุรี 20131
[1] Department of Industrial Engineering, Faculty of Engineering, Burapha University, Saensuk Municipality, Muang District, Chonburi Province, 20131, Thailand
[2] Department of Advanced Materials Engineering, Faculty of Engineering, Burapha University, Saensuk Municipality, Muang District, Chonburi Province, 20131, Thailand
[*] Corresponding author: sunisak@eng.buu.ac.th

aluminum alloy increased with the addition of Si and Mg powders. As the Mg content increased from 1.5 wt.% to 3 wt.%, the volume fraction of the $Al_{19}(Mg_2Si)$ secondary phase increased. The experimental results indicated that the addition of Si and Mg can modify the microstructure and improve the mechanical properties of the recycled aluminum alloy.

Keywords: Aluminum beverage cans, recycled aluminum alloy, Al-Mg-Si alloy, microstructure, mechanical property

Introduction

Aluminum alloy is a metal with many outstanding properties, such as a lightweight, high ductility, good corrosion resistance, and recyclability (Sharma *et al*., 2020). Hence, it is widely used in a wide range of applications, such as automotive parts, electrical appliance parts, window frames, and food packaging (Sharma *et al*., 2020, Miller *et al*., 2000, Borgert & Homberg, 2022, Cooper & Allwood, 2012, Brough & Jouhara, 2020). Based on reports, 50.6 million tons of aluminum alloy products were used in 2013, the need for these consumptions has increased to 59 million tons by 2016, and the demand for aluminum alloy products tends to grow every year (Galevsky *et al*., 2018). Thus, aluminum alloy wastes are increasing, especially the wastes from food packaging with single-use products (i.e., beverage cans, aluminum foil, and food cans). Common waste disposal methods are reuse, composting, recycling, and sanitary landfill (Sakai *et al*., 1996). Recycling is probably the most beneficial method for aluminum and its alloy waste disposal. Recycling aluminum uses only 5% of the energy expended to produce the aluminum from bauxite ore and produces carbon dioxide lower than primary aluminum production by 20 times (Raabe *et al*., 2022). Hence, it could be a promising method to sustain environmentally friendly aluminum products and is beneficial for a country that does not have much bauxite ore reserves.

Aluminum beverage cans were invented in 1959 as alcoholic drink containers (Buffington & Peterson, 2013). A beverage can made of aluminum alloy is lighter, has higher corrosion resistance, and make drinks much cooler than steel cans in a short span of time. The shape of the aluminum beverage cans has been continuously modified to meet consumer needs (Hosford & Duncan, 1994). Aluminum beverage cans are composed of two parts: can body and can lip. Many researchers have reported that the can body and can lid parts are made of aluminum alloy grade 3004 and aluminum alloy grade 5182, respectively (Dagwa & Adama, 2018, Alsaffar & Bdeir, 2008, Risonarta *et al*., 2019, Padmanabhan *et al*., 2011).

Nowadays, recycle of used aluminum beverage cans could be conducted via two techniques: (i) melting the main body and lid parts separately and (ii) melting the beverage can without disassembling it (Hosford & Duncan, 1994, Dagwa & Adama, 2018, Alsaffar & Bdeir, 2008, Risonarta *et al*., 2019, Padmanabhan *et al*., 2011). From an economical point of view, the second recycling method appears to be the most effective way to recycle aluminum beverage cans at a low cost. This approach is easy to perform and consumes a short operation time. The recovery mass of recycled aluminum via this technique is 52.5% - 59.1% (Alsaffar & Bdeir, 2008). However, in this method a recycled aluminum alloy ingot has complex physical and chemical properties because it was casted from two different aluminum alloys. The ingot has a Mg, Mn, and other trace elements with incompatible content from the trace aluminum alloy. Therefore, the properties of the recycled aluminum alloy ingot must be improved to enhance its mechanical properties and become a commercial aluminum alloy. The most widely used method for improving the performance of aluminum alloy ingots is the addition of alloying elements (e.g., Mg, Si, Cu Fe, and Cr) (Rana *et al*., 2012). However, the type and quantity of the alloying elements significantly affect the aluminum alloys' properties (Jiang *et al*., 2020, Simsek & Özyürek, 2019, Wang *et al*., 2014). Moreover, aluminum has a solubility limit. Hence, the addition of an excess quantity would create a different secondary phase and reflect the physical and mechanical properties of an ingot. Improving the properties of recycled aluminum beverage cans by adding alloying elements has been rarely studied.

Therefore, this research aims to investigate the properties of recycled aluminum beverage cans and improve their properties with the addition of Si and Mg elements. The Si and Mg elements were added to enhance the mechanical properties and modify the chemical composition of recycled aluminum alloys. The microstructure and mechanical properties of the recycled aluminum alloy and recycled Al-Mg-Si alloy were systematically studied. The role of Si and Mg on the changes in the microstructure and mechanical properties of the aluminum alloy were also examined.

Materials and methods

Raw materials

Used aluminum beverage cans were utilized in this study. The chemical compositions of the can lid and can body are shown in Table 1. The used aluminum beverage cans were recycled in seven steps: (i) clean the used cans with water, (ii) compress the cleaned cans into small pieces (Figure 1(a)), (iii) put them in a refractory crucible (Figure 1(b)), (iv) melt them in a gas furnace (Figure 1(c)), (v) add flux to the melt to remove impurities, (vi) pour the molten into a rectangle permanent steel mold (with a dimension of 45 × 150 × 30 mm^3), and (vii) quench using water to room temperature. The recycled aluminum alloy ingots were used as initial materials. The chemical composition of the ingots was determined using the emission spectroscopy model Thermo ARL 3460. The results of the as-cast recycled aluminum beverage can specimen (defined as the as-cast recycled Al alloy) are shown in Table 2.

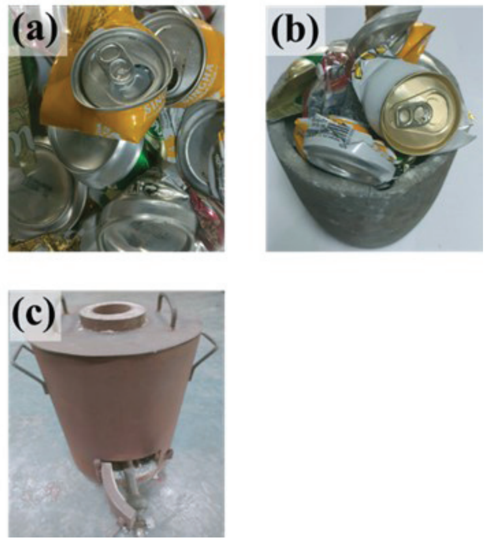

Figure 1 Raw materials and equipment used in this study: (a) compressed aluminum beverage cans, (b) refractory crucible, and (c) gas furnace.

Table 1 Chemical composition of the can body and lid used in this study (wt.%).

Part	Mg	Mn	Fe	Si	Al
Investigated from the as-cast ingot					
Body	0.72	0.96	0.44	0.29	Bal.
Lid	3.51	0.34	0.25	0.10	Bal.
From the literature reviews					
Body (Al3004)	1.0	1.2			Bal.
Lid (Al5182)	4.5	0.35	0.26		Bal.
(Alsaffar & Bdeir, 2008)					
Body	4.82	0.27	0.26		Bal.
Lid	2.53	0.33	0.32		Bal.
(Risonarta *et al.*, 2019)					

Table 2 Chemical composition of the as-cast recycled Al alloy (wt.%).

Mg	Mn	Fe	Si	Cu	Zn	Al
1.26	0.86	0.43	0.28	0.17	0.06	Bal.

Experimental procedure

The as-cast recycled Al alloy ingot was cut into small pieces. The magnesium powder with a purity of 99.9% and mean particle size of 177 μm was used as a reinforced alloying element of the recycled Al alloy. A commercial silicon powder with an average particle size of 56 μm was also used as a reinforced alloying element. The mixture composition in this study is reported in Table 3 The sectioned ingots were melted at 750 ± 5 °C in the electrical furnace under an ambient atmosphere. Then Mg and Si powders were added to the melt at different amounts to improve the properties of the recycled Al alloy and investigate the role of Mg and Si on the evolution of the microstructure and mechanical properties in the recycled Al alloy. Afterward, the mixture was stirred for two minutes, cast in a preheated (550 °C) 14 mm in diameter permanent steel mold, and then water quenched to room temperature.

Table 3 The mixture composition of Mg and Si particles reinforced the recycled Al alloy.

Alloy	Element (wt.%)		
	Recycled Al alloy	Mg	Si
Recycled Al alloy	100		
Al-0.25%Si	99.75		0.25
Al-0.5%Si	99.50		0.50
Al-1.5%Mg	98.50	1.50	
Al-3%Mg	97.00	3.00	
Al-1.5%Mg-0.25%Si	98.25	1.50	0.25
Al-1.5%Mg-0.5%Si	98.00	1.50	0.50
Al-3%Mg-0.25%Si	96.75	3.00	0.25
Al-3%Mg-0.5%Si	96.50	3.00	0.50

Characterization and Property testing

Density analysis

The density and porosity of the as-cast recycled Al alloy and recycled Al-Mg-Si alloy specimens were evaluated and computed using Equations (1) and (2) (Michailidis & Stergioudi, 2011):

$$\rho_s = \frac{m}{V} \quad (1)$$

$$Porosity = 1 - \frac{\rho_s}{\rho_t} \times 100 \quad (2)$$

$$\rho_t = \rho_{RA} V_{RA} + \rho_{Mg} V_{Mg} + \rho_{Si} V_{Si} \quad (3)$$

where p_s is the density of a specimen (g/cm^3) ; *m* is the mass of the specimen evaluated using a digital balance (g) ; *V* is the volume of the specimen computed from its dimension (cm^3) ; p_t is the total theoretical density of specimen ; p_{RA} is the theoretical density of the recycled Al alloy, which was computed based on its chemical composition (2.761 g/cm^3) ; p_{Mg} and p_{Si} are the densities of Mg and Si (i.e., 1.7 and 2.33 g/cm^3) ; V_{RA}, V_{Mg} and V_{Si} are the volume fractions of the recycled Al alloy, Mg, and Si elements, respectively.

Microstructural evaluation

The microstructure of the as-cast recycled Al alloy and recycled Al-Mg-Si alloy specimens were characterized via light optical microscopy (LOM) and using the scanning electron microscopy (SEM) model FEI Quanta 450 equipped with an energy dispersive spectrometer (EDS X-Max). LOM was used to examine the morphology and distribution of the secondary phase in the casted specimens. With SEM having a better resolution, it is used to obtain a precise characterization of the formation of the secondary phase during the casting process.

The specimens for the microstructural observation were mechanically polished using SiC paper no. 400, 600, 800, 1,000, and 1,200 grits, followed by alumina powder particle with sizes of 0.5, 0.3, and 0.05 μm.

Mechanical properties

The hardness and tensile strength of the specimens were evaluated using the hardness tester equipped with a Brinell indenter model INNOVATEST Europe BV and universal testing machine model NRI-TS500-50B. The hardness specimens were mechanically polished using SiC paper ranging from 400 to 1,000 grits. The hardness test was performed on the polished surface of the specimens. A steel ball indenter with a diameter of 2.5 mm, load of 16.25 kgf, and dwelling time of 10 s was applied in all the specimens. The tensile test specimens were prepared according to the tensile test specimen standard ASTM E8, with 6 ± 0.1 mm in diameter and 24 ± 1 mm gauge length. A tensile test was conducted at a constant crosshead speed of 1 mm/min under ambient temperature.

Estimation cost

In this study, the cost of a recycled Al alloy was computed using Equation (4) (Apisithpinyo, 2006). Five repeat experiments were conducted in each study. The production yield of the recycled Al alloy was also investigated by Equation (5) (Risonarta *et al.*, 2019):

$$\text{Estimation cost} = DM + DL + OH \quad (4)$$

$$\text{Production yield} = \frac{m_{out}}{m_{input}} \quad (5)$$

where *DM* is the direct materials cost, *DL* is the direct labor cost and *OH* is the manufacturing overhead cost, m_{out} is the mass of the recycled Al alloy ingot, and m_{input} is the mass of the used aluminum beverage cans. The prices of the used aluminum beverage can, liquefied petroleum gas, and labor cost were 40 baht/kg, 21.50 baht/kg and 40 baht/h, respectively. In particular, the *OH* cost in this study was computed from the main equipment depreciation only. The gas furnace and refractory crucible prices were 60,000 and 1,200 baht., respectively. The salvage value of all equipment was estimated as 60% of the product price. Therefore, the overhead cost computed based on the above data was estimated to be 30 baht/time.

Results and discussion

Density and porosity analysis

The density and porosity of the as-cast recycled Al alloy and recycled Al-Mg-Si alloy specimens are shown in Figure 2. It was found that the density of the as-cast recycled Al alloy was 2.73 g/cm^3

The density of the specimens decreased from 2.73 g/cm^3 to 2.71 g/cm^3 when 0.25 wt.% Si powder was added. By further increasing the Si powder content to 0.5 wt.%, the density of the specimens gradually decreased to 2.70 g/cm^3. Similar results were also observed in the added Mg powder specimen, where the density specimen decreased with the increase in the Mg powder content. At 0.5 wt.% Si and 3 wt.% Mg addition, the density reduced by approximately 3% compared to the as-cast recycled Al alloy. This is attributed to the Si and Mg having a density (i.e., 2.33 and 1.7 g/cm^3) lower than that of the as-cast recycled Al alloy (2.73 g/cm^3). Hence, the addition of Si and Mg powders caused a decrease in the recycled Al alloy density. The porosity results in Figure 2 also reveal that the porosity of the specimens tended to increase when Si and Mg powders were added. With the addition of 1.5 and 3 wt.% Mg powders, the porosity rose from 1.27% to 1.74% and 2.13%, respectively. The increasing porosity in the recycled Al-Mg-Si specimen may cause by the fabrication method (Khamsuk *et al.*, 2020) and the rise of Mg and Si powder content. In this study, a stirring process was used to mix magnesium and silicon powders in molten recycled Al alloy to disperse those alloying powders evenly in the specimen. This process generally creates gas bubbles in the melt, those bubbles might get trapped in the specimen and become a pore. Meanwhile, the addition of Mg and Si powder in recycled Al alloy casting also caused gas bubbles and enhanced hydrogen solubility in the molten recycled Al alloy (Jang *et al.*, 2019). So, the amount of porosity in the specimen increased with increasing the Mg and Si powder content.

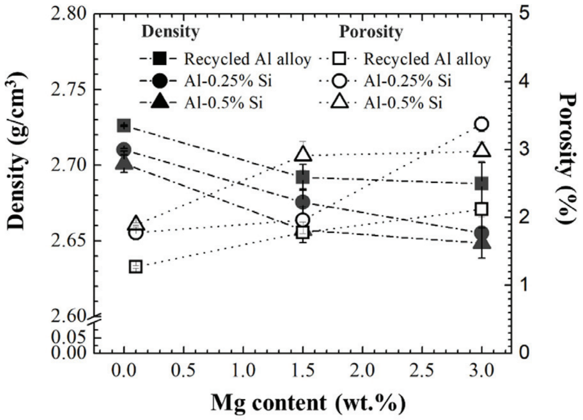

Figure 2 Density and porosity of the as-cast recycled Al alloy and recycled Al-Mg-Si at different Si and Mg contents.

Microstructural observation

The microstructures of the as-cast recycled Al alloy and recycled Al-Mg-Si alloy at different amounts of Si and Mg content specimens are shown in Figure 3. The as-cast recycled Al alloy specimen consisted of a dendrite microstructure and secondary phases localized at the dendrite boundary (Figure 3(a)). With the addition of 0.25 wt.% Si, the grain size of the specimens decreased (Figure 3(b)). By increasing the Si content to 0.5 wt.%, grain size gradually decreased and dark particle secondary phase was observed (Figure 3(c)). The microstructure of the recycled Al alloy obviously changed when Mg powders were added (Figure 3(d)-(i)). With the addition of 1.5 wt.% Mg, the specimen had a finer and higher volume fraction in the secondary phase (Figure 3 (d)) compared to those in the non-Mg added Al alloy specimen (Figure 3(a)-(c)). Furthermore, the secondary phase was homogeneously distributed throughout the specimen. Figure 3(e) and (f) show that the volume fraction of the secondary phases in the Al-0.25%Si-1.5%Mg and Al-0.5%Si-1.5%Mg specimens were higher than that of the Al-1.5%Mg specimens (Figure 3(d)). With the future increase of the Mg content to 3 wt.%, the size of the second phase became finer and more abundant. The results indicated that the addition of Mg and Si led to refining the recycled Al alloy structure and increased the amount of fine second phases. Birol (2012) has also found a similar result: a coarse grain structure of an Al-Mg alloy ingot completely transformed to a fine grain structure when 2 wt.% Mg was added. This result is attributed to the addition of Mg and Si powder reducing the solidification interval and solute atoms inhibit a grain boundary motion resulting in a fine grain (Birol, 2012). The increase in the secondary phase may be due to an increase in the interaction between the added Mg and Si and alloying elements in the recycled Al alloy. The morphology and chemical compounds of the secondary phase were studied using SEM.

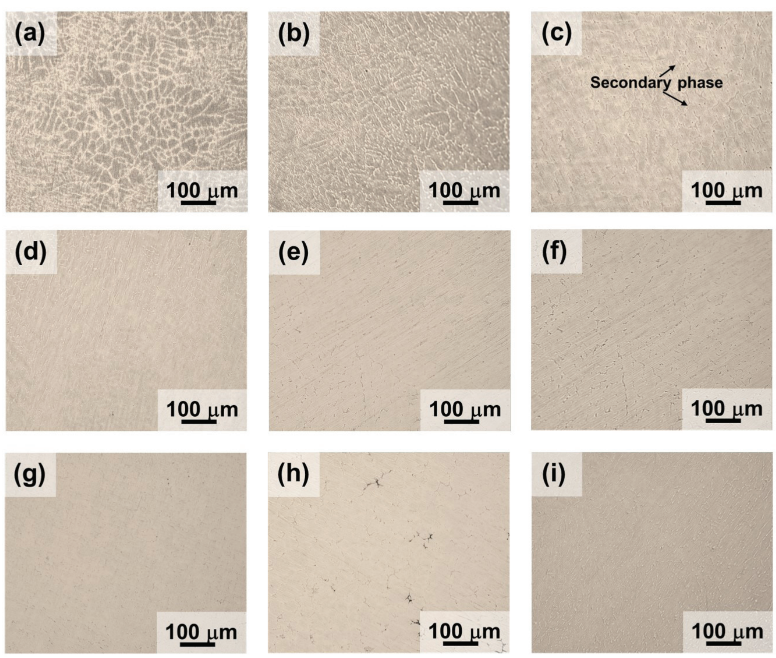

Figure 3 Microstructure of (a) the as-cast recycled Al alloy, (b) Al-0.25%Si, (c) Al-0.5%Si, (d) Al-1.5%Mg, (e) Al-1.5%Mg-0.25%Si, (f) Al-1.5%Mg-0.5%Si, (g) Al-3%Mg, (h) Al-3%Mg-0.25%Si, and (i) Al-3%Mg-0.5%Si specimens.

The SEM micrographs of the as-cast recycled Al alloy and recycled Al-Mg-Si alloy at different Si and Mg contents are shown in Figure 4. Figure 4 (a) shows that the as-cast recycled Al alloy specimen is composed of four different secondary phases (i.e., a light particle (indicated by a white dotted circle-1), long light particle (circled-2), Chinese-script (circled-3), and dark particle (circle-4)) distributed in the Al alloy solid solution. The microstructures of the specimens examined via SEM were similar to the LOM observation results. The volume fraction of the fine secondary phases increased with increasing Si and Mg contents.

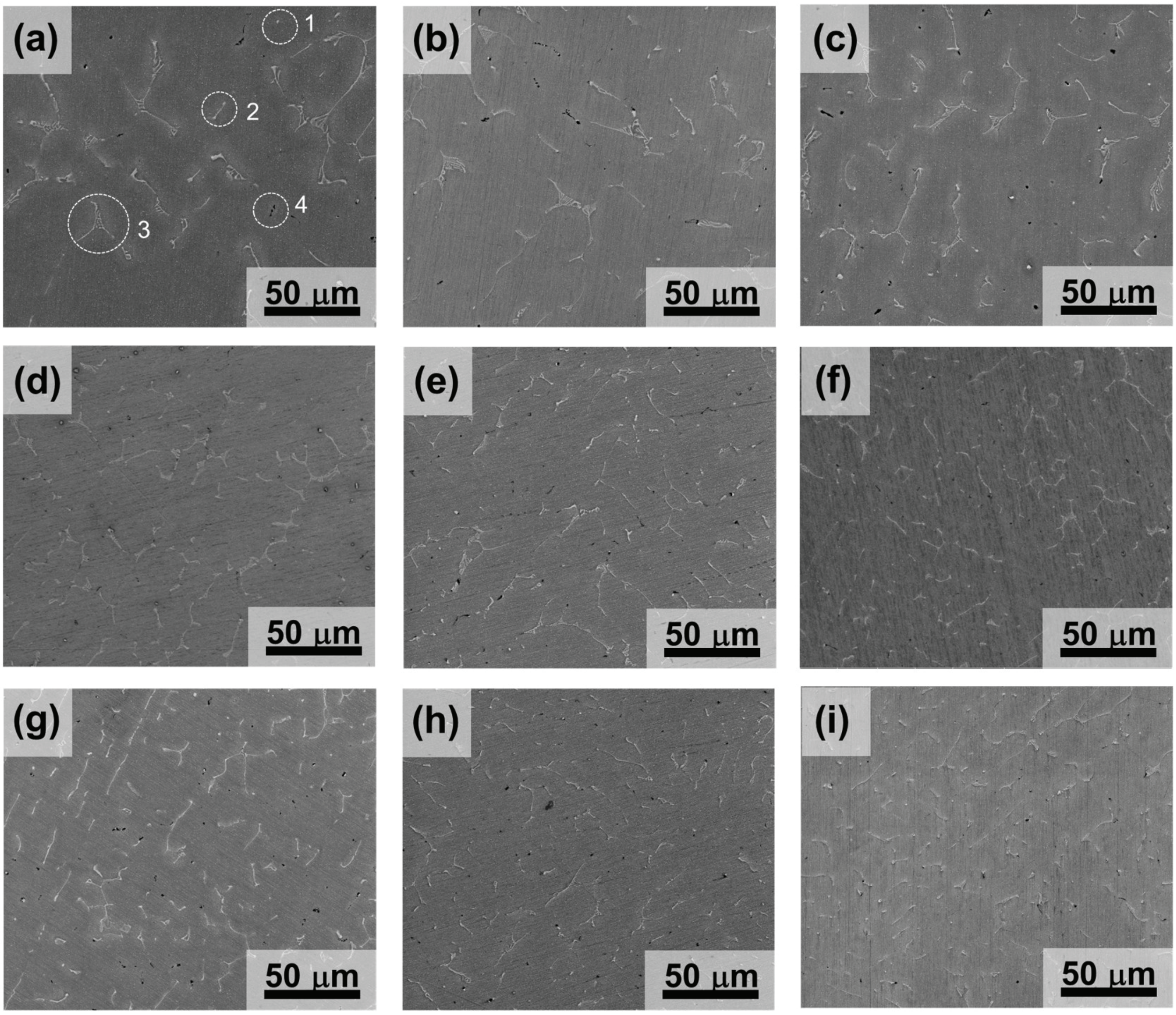

Figure 4 SEM micrograph of (a) the as-cast recycled Al alloy, (b) Al-0.25%Si, (c) Al-0.5%Si, (d) Al-1.5%Mg, (e) Al-1.5%Mg-0.25%Si, (f) Al-1.5%Mg-0.5%Si, (g) Al-3%Mg, (h) Al-3%Mg-0.25%Si, and (i) Al-3%Mg-0.5%Si specimens.

The EDS analysis indicated that the secondary phase in the white dotted circle-1 was an intermetallic $Al_{19}Fe_3SiMn$ phase (Figure 5 (a)), the long light particle was an intermetallic $Al_{33}Fe_3SiMn$ phase (Figure 5 (b)), the Chinese-script particle was an $Al_{11}Fe_2Mn$ phase (Figure 5 (c)), and the dark particle was an $Al_{19}(Mg_2Si)$ phase (Figure 5 (d)). The chemical composition of the recycled Al alloy solid solution phase was also identified. The Al alloy phase consisted of 1.0 wt.% Mg and 0.7 wt.% Mn (Figure 5 (e)). This result is well consistent with the analytical results of spectrometer in Table 2. It is also clearly seen from Figure 4 that the intermetallic $Al_{19}(Mg_2Si)$ phase increased with the increasing Mg and Si contents.

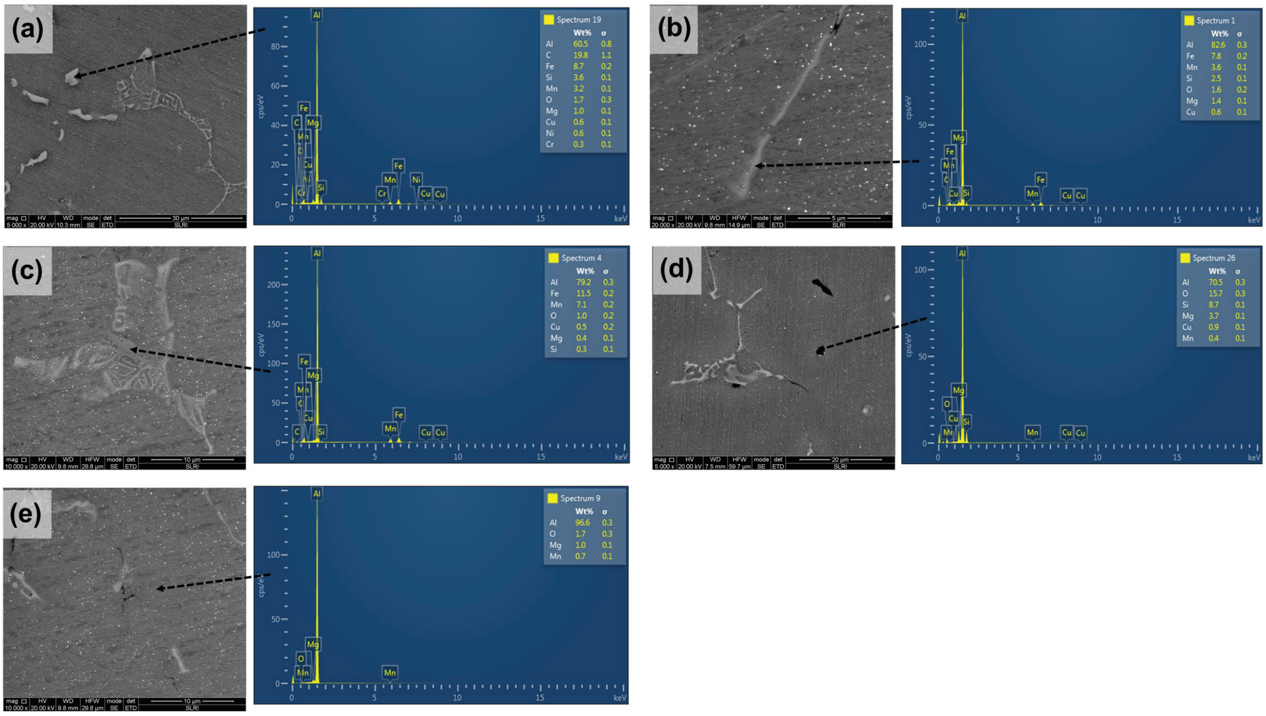

Figure 5 EDS analysis of the casted Al alloy at (a) light particle ($Al_{33}Fe_3SiMn$), (b) light long particle ($Al_{11}Fe_2Mn$), (c) Chinese-script particle ($Al_{11}Fe_2Mn$), (d) dark particle ($Al_{19}(Mg_2Si)$), and (e) solid solution position.

Hardness and tensile testing

The hardness values obtained from the as-cast recycled Al alloy and recycled Al-Mg-Si alloy at different Si and Mg contents specimens are shown in Figure 6. The hardness values of the recycled aluminum beverage cans mixed with 2 wt.% Mg powder (Hayyawi *et al*., 2016) and similar chemical composition materials (Li *et al*., 2016, Alizadeh *et al*., 2022) are also plotted in Figure 6 for comparison. The as-cast recycled Al alloy ingot obtained by recycling from used aluminum beverage cans under this production condition has a hardness of approximately 40.67 ± 2 HB. When the Si contents were 0.25 and 0.5 wt.%, the hardness of the Al alloys increased to 44.03 and 47.15 HB, respectively. The hardness of the specimens increased to 50.67 and 55.36 HB when 1.5 and 3 wt.% Mg was added, respectively. With the addition of both alloying elements, the hardness of the recycled Al alloys was raised, and a hardness of 59.60 HB was obtained in the Al-3%Mg-0.5%Si specimens. It was also found in this study that the hardness value of the Al-3%Mg-025%Si specimen is comparable to that of a casted Al5083 alloy (Alizadeh *et al*., 2022). These results revealed that an Al alloy produced by recycling used beverage cans could improve its chemical composition and hardness to be comparable to Al5083 by the addition of Si and Mg. These results also indicate that the addition of Si and Mg enhanced the hardness of the recycled Al alloy. The result obtained was similar to research works done by other researchers using Mg as an additional alloying element in aluminum alloy casting manufacturing (Simsek & Özyürek, 2019, Li *et al*., 2016).

Figure 7 showed the ultimate tensile strength and elongation of the as-casted recycled Al alloy and recycled Al-Mg-Si alloy at different amounts of Si and Mg contents. The as-casted recycled Al alloy has an approximately ultimate tensile strength of 77.72 ± 8 MPa. The tensile strength increased with increasing Si and Mg contents. From the result of Figure 7, it could be observed that the addition of 0.5 wt.% Si and 3 wt.% Mg powders improve the ultimate tensile strength of the Al alloy to 129.78 ± 5 MPa. The tensile test results are well consistent with those of the hardness properties. Meanwhile, the elongation of the recycled Al alloy decreased with increasing amount of the Si and Mg contents.

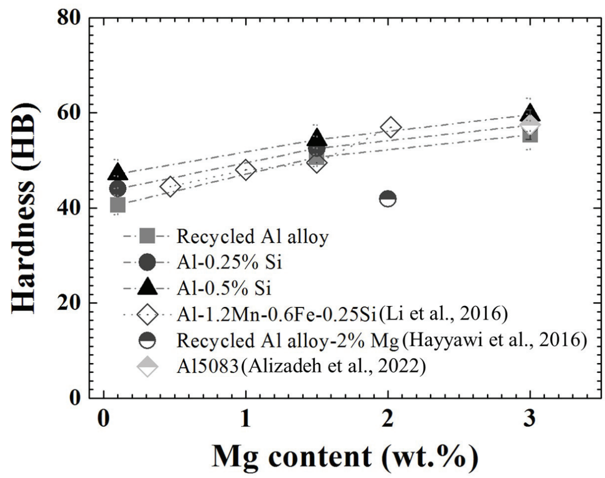

Figure 6 Hardness of the as-cast Al alloy and recycled Al-Mg-Si alloy plotted as a function of the Mg content.

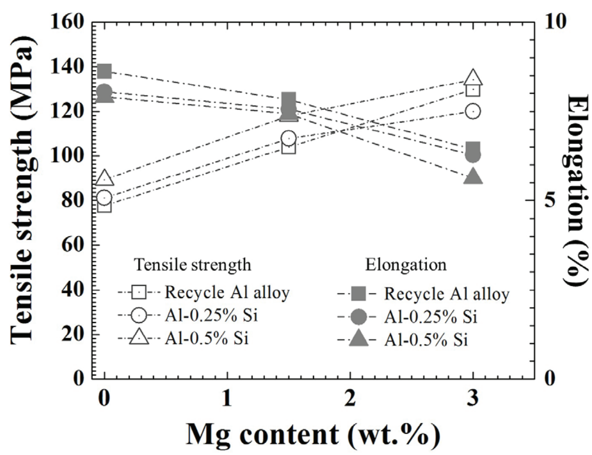

Figure 7 Ultimate tensile strength of the as-cast Al alloy and recycled Al-Mg-Si alloy plotted as a function of Mg content.

The enhanced strength of the recycled Al alloy was caused by the addition of Mg and Si contents leading to the acceleration of the intermetallic phase refinement, raised volume fraction of intermetallic phases and formation of fine grain structure in the specimen. In particular, those that presented intermetallic phases and grain boundary inhibited dislocation motion. The increase in the strength can also be explained by the secondary phase strengthening (σ_{sp}) and grain size reduction strengthening (σ_{gb}) mechanisms in Equation 6-7 (Esmaeili *et al.*, 2013):

$$\sigma = \sigma_{s\rho} + \sigma_{gb} \tag{6}$$

$$\sigma = \frac{MF(f)^{1/2}}{br} + k_y d^{-1/2} \tag{7}$$

where M stands for the Taylor factor, F is the secondary phase strength, f is the volume fraction of the secondary phase, b is the Burgers vector, r is the precipitate radius, k_y is the Hall-Petch slope, and is the grain size.

The addition of Si and Mg alloying elements led to an increase in the volume fraction of the fine secondary phase and reduced the grain size which resulted in improving the strength of the recycled Al alloy.

Estimation cost

In this study, the used aluminum beverage cans were melted in a refractory crucible with a 12 cm diameter and 17 cm height using a gas furnace (25 cm in diameter and 45 cm in height) under a melting temperature of 900 ± 50 °C. Each cycle of the recycling process used 8 ± 0.1 kgs of used aluminum beverage cans and 6.8-7.4 kgs of liquefied petroleum gas. The production cost of the recycled Al alloy ingot was 156-168 baht/kg. which is compatible with the estimated Al recycling cost reported by Zeng *et al.* (2022). Recycling one ton of aluminum requires approximately 435-3,802 USD. However, it should be noted here that the raw material cost, labor cost, and overhead cost in the USA is significantly higher than in Thailand. Hence, the production cost in this study is relatively high. This condition is ascribed to the recycling process in this study, which is a small-scale production, resulting in high costs, and the main cost was the labor cost. The production yield obtained from the recycled aluminum beverage cans was 53%-55%. The recycling yield was slightly low. This may be due to the cans containing high impurity content such as paint coatings, aluminum oxide, and alloying elements. Furthermore, the recycling process was carried out under ambient air which caused the formation of aluminum oxide on the molten surface in large quantities. The production yield might probably be enhanced by controlling the recycling atmosphere condition and removing the paint coatings prior melting process.

Conclusions

The used aluminum beverage cans were recycled using a gas furnace. The properties of the as-cast recycled Al alloy were systematically investigated. Si and Mg powders were used to improve the properties of the recycled Al alloy. The evolution of the microstructure and mechanical properties of the recycled Al alloys at different Si and Mg contents were investigated. The conclusions can be summarized as follows:

1. The recycled Al alloy ingot mainly contained 1.26 wt.% Mg and 0.86 wt.% Mn and had a tensile strength of approximately 77 MPa. The microstructure of the ingot composed of $Al_{19}(Fe_3SiMn)$, $Al_{33}(Fe_3SiMn)$, $Al_{11}(Fe_2Mn)$, and $Al_{19}(Mg_2Si)$ phases distributed in the Al-Mg solid solution.

2. The microstructure greatly changed when 1.5 wt.% Mg was added to the recycled Al alloy. The volume fraction of the fine secondary phases increased with increasing Mg and Si contents. The amount of the $Al_{19}(Mg_2Si)$ secondary phase raised with increasing alloying elements. The addition of Mg and Si enhanced the grain refinement in the recycled Al alloy.

3. The tensile strength and hardness of the recycled Al alloy specimens increased with increasing Mg and Si contents. The hardness increased by approximately 46% when 3 wt.% Mg and 0.5 wt.% Si were added.

4. The estimated cost and production yield of the recycled Al alloy from the used aluminum beverage cans were 156 - 168 baht/kg and 53% - 55%.

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References

Alizadeh, A., Khayami, A., Karamouz, M., & Hajizamani, M. (2022). Mechanical properties and wear behavior of Al5083 matrix composites reinforced with high amounts of SiC particles fabricated by combined stir casting and squeeze casting ; A comparative study. *Ceramics International, 48*, 179-189. https://doi.org/10.1016/j.ceramint.2021.09.093

Alsaffar, K.A., & Bdeir, L.M.H. (2008). Recycling of aluminum beverage cans. *Journal of Engineering and Development, 12*, 157-163.

Apisithpinyo, B. (2006). *Cost accounting II*. Idea software technology.

Birol, Y. (2012). Effect of solute Mg on grain size of aluminium alloys. *Materials Science and Technology, 28*, 924-927. DOI:10.1179/174 3284712Y.0000000024

Borgert, T., & Homberg, W. (2022). Energy saving potentials of an efficient recycling process of different aluminum rejects. *Energy Reports, 8*, 399-404. https://doi.org/10.1016/j.egyr.2022.01.027

Brough, D., & Jouhara, H. (2020). The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. *International Journal of Thermofluids, 1-2*, 1-36. https://doi.org/10.1016/j.ijft.2019.1000 07

Buffington, J., & Peterson, R. (2013). Defining a closed-Loop U.S. aluminum can supply chain through technical design and supply chain innovation. *The Journal of The Minerals, Metals & Materials Society (TMS), 65*, 941-950. https://doi.org/10.1007 /s11837-013-0615-2

Cooper, D.R., & Allwood, J.M. (2012). Reusing steel and aluminum components at end of product life. *Environmental Science &Technology, 18*, 10334-10340. https://doi.org/10.1021/es301093a

Dagwa, I.M., & Adama, K.K. (2018). Property evaluation of pumice particulate-reinforcement in recycled beverage cans for Al-MMCs manufacture. *Journal of King Saud University - Engineering Sciences, 30*, 61-67. https://doi.org/10.1016/j.jksues.2015.12.006

Esmaeili, S., Lloyd, D.J., & Poole, W.J. (2003). A yield strength model for the Al-Mg-Si-Cu alloy AA6111. *Acta Materialia, 51*, 2243-22 57, https://doi.org/10.1016/S13596454(03)00028-4

Galevsky, G.V., Rudneva, V.V., & Aleksandrov, V.S. (2018). Current state of the world and domestic aluminium production and consumption. IOP Conference Series: Materials Science and Engineering: Vol. 411. *The 20th International Scientific and Research Conference "Metallurgy: Technologies, Innovation, Quality. Metallurgy-2017* (pp. 1-6). Novokuznetsk, Russia. doi:10.1088/1757-899X/411/1/012017

Hayyawi, A.R., Al-Ethari, H., & Haleem, A.H. (2016). Investigation of mechanical & machining properties of recycled Al-Fly ash composites. *Advances in Natural and Applied Sciences, 10*, 50-59.

Hosford, W.F., & Duncan, J.L. (1994). The aluminum beverage can produced by the hundreds of millions every day, the modern can robust enough to support the weight of an average adult is a tribute to precision design and engineering. *Scientific American, 271*, 48-53.

Jang, H.S., Kang, H.J., Yoon, P., Lee, G., Jeon, J.B., Park, J.Y., Kim, E.S., & Shin, S. (2019). Effects of Mg content on hydrogen content and melt quality of Al-Mg alloys. *Metals, 9*, 1-13. https://doi.org/10.3390 /met9111235

Jiang, B., Xu, S., Xu, H.Y., Hu, M.L., He, Y.J., & Ji, Z.S. (2020). Effect of Mg addition on microstructure and mechanical properties of Al-Si-Cu-Fe alloy with squeeze casting. *Materials Research Express, 7*, 1-9. https://doi.org/10.1088/2053-1591/ab5cc6

Khamsuk, S., Nakvachiratrakul, C., & Chomsaeng, N. (2020). Fabrication and characterization of Al5083-2 wt.% SiO_2 composite and its aging behavior. In Maensiri, S., Meevasana, W., & Pecharapa, W (Eds.), *AIP Conference Proceedings: Vol.2279. The second materials research society of Thailand international conference* (pp. 1-5). Pattaya, Thailand. https://doi.org/10.1063/5.0022966

Li, Z., Zhang, Z., & Chen, X.G. (2016). Effect of magnesium on dispersoid strengthening of Al—Mn—Mg—Si(3xxx) alloys. *Transactions of Nonferrous Metals Society of China, 26*, 2793-2799. https://doi.org/10 .1016/S1003-6326(16)64407-2

Michailidis, N., & Stergioudi, F. (2011). Establishment of process parameters for producing Al-foam by dissolution and powder sintering method. *Materials & Design, 32*, 1559-1564, https://doi.org/10.1016/j.matdes.2010.09.029

Miller, W.S., Zhuang, L., Bottema, J., Wittebrood, A.J., De Smet, P., Haszler, A., & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering: A, 28*, 37-49. https://doi.org /10.1016/S0921-5093(99) 00653-X

Padmanabhan, R., Oliveira, M.C., & Menezes, L.F. (2011). 5-Lightweight metal alloy tailor welded blanks. In Woodhead Publishing Series in Welding and Other Joining Technologies, B. L. Kinsey, & X. Wu (Eds.), *Tailor Welded Blanks for Advanced Manufacturing* (pp. 97-117). Woodhead Publishing. https://doi.org/10.1533/978085 7093851.2.97

Raabe, D., Ponge, D., Uggowitzer, P.J., Roscher, M., Paolantonio, M., Liu, C., Antrekowitsch, H., Kozeschnik, E., Seidmann, D., Gault, B., Geuser, F.D., Deschamps, A., Hutchinson, C., Liu, C., Li, Z., Prangnell, P., Robson, J., Shanthraj, P., Vakili, S., Sinclair, C., Bourgeois, L., & Pogatscher, S. (2022). Making sustainable aluminum by recycling scrap: The science of "dirty" alloys. *Progress in Materials Science, 128*, 1-150. https://doi.org/10.1016/j.pmatsci.20 22.100947

Rana, R.S., Purohit, R., & Das, S. (2012). Review on the influences of alloying elements on the microstructure and mechanical properties of aluminum alloys and aluminum alloy composite. *International Journal of Scientific and Research Publications, 2*, 1-7.

Risonarta, V.Y., Anggono, J., Suhendra, Y.M., Nugrowibowo, S., & Jani, Y. (2019). Strategy to Improve Recycling Yield of Aluminium Cans. E3S Web Conf: Vol. 130. *The 1st International Conference on Automotive, Manufacturing, and Mechanical Engineering (IC-AMME 2018)* (pp. 1-8). Bali. Indonesia. https://doi.org/10.1051/e3 sconf/201913001033

Sakai, S., Sawell, S.E., Chandler, A.J., Eighmy, T.T., Kosson, D.S., Vehlow, J. Van Der Sloot, H.A., Hartlén, J., & Hjelmar, O. (1996). World trends in municipal solid waste management. *Waste Management, 16*, 341-350. https://doi.org/10.1016/S0956-053X(96)00106-7

Simsek, I., & Özyürek, D. (2019). Investigation of the effects of Mg amount on microstructure and wear behavior of Al-Si-Mg alloys. *Engineering Science and Technology, an International Journal, 22*, 370-375. https:// doi.org/10.1016/j.jestch.2018.08.016

Sharma, A.K., Bhandari, R., Aherwar, A., Rimašauskiene, R., & Pinca-Bretotean, C. (2020). A study of advancement in application opportunities of aluminum metal matrix composites. *Materials Today: Proceedings, 26,* 2419-2424. https://doi.org/10.1016/j.matpr.2020.02.516

Wang, Y., Liao, H., Wu, Y., & Yang, J. (2014). Effect of Si content on microstructure and mechanical properties of Al-Si-Mg alloys. *Materials & Design, 53*, 634-638, https:// doi.org/10.1016/j.matdes.2013.07.067

Zeng, X., Xiao, T., Xu, G., Albalghiti, E., Shan, G., & Li, J. (2022). Comparing the costs and benefits of virgin and urban mining. *Journal of Management Science and Engineering, 7*, 98-106, https://doi.org/10.1016/j.jmse.2021.05.002