Innovative Scandium Recovery Method from Metallic End Life Products

Bengi YAGMURLU [1,2], Carsten DITTRICH [1], Grenvil DUNN [3]

[1] MEAB Chemie Technik GmbH, Aachen, Germany
[2] IME Institute of Process Metallurgy and Metal Recycling, RWTH Aachen, Aachen, Germany
[3] Hydromet WA, Perth, Australia

bengi.yagmurlu@meab-mx.com, carsten.dittrich@meab-mx.com, grenvil.dunn@hydrometwa.com

Abstract

Scandium (Sc) which is an extremely expensive element for large-scale industrial use at the moment, has attracted attention in the last decade due to property improvements in the alloy and in the energy sector. As a result of scarce direct sources, Sc is generally produced as a by-product of rare earth elements (REEs), uranium (U), titanium dioxide and nickel laterite. Other than natural sources, end-life products that contain Sc could be another important source in near future as the application area of Sc is expected to be increased. However, processing electronegative metals such as Al and Sc via hydrometallurgical operations results in aggressive and extremely exothermic reactions. This uncontrollable reaction makes the larger scale operations harder to apply and adapt. In this study, a novel hydrometallurgical processing route is presented with the intention to recover Sc from alloy powders that contains Sc. Thus, an innovative leaching approach was applied employing a metal salt solution with higher reduction potential to dissolve the metallic powders with cementation of the metal from the leaching solution. Almost complete dissolution of the metallic particles was observed with this strategy. Then, Sc was separated and purified from the impurities by solvent extraction.

Introduction

With the upcoming limitations on gasoline-based vehicles, especially in Europe under the Paris Accord[1], research on lightweight alloys for lower CO_2 emission and efficient electrical cars has peaked. Since Aluminium (Al) is the most abundant metal in the earth crust with no accessibility problems and low price, Al alloys take the lead on design of lightweight alloys. Even though it has several disadvantages such as low strength, incompatibility for welding and low thermal stability, these physical and mechanical properties could be enhanced through alloying.

Scandium (Sc) which is an extremely expensive element for large-scale industrial use at the moment, has attracted attention in the last decade due to property improvements in the alloy and in the energy sector and was hence classified as a critical metal for the future[2-6]. Sc reinforced Al alloys display plentiful advantages over high strength Al alloys and represent a new generation of advanced materials. Addition of minor amount of Sc could tune and enhance the properties of Al alloys, majorly as an outcome of the formation of Al_3Sc phase. Additionally, the mechanical properties of the material could be improved as a result of recrystallization resistance by Sc addition to Al alloys[7]. The problems occurring during welding such as soft spots and loss of strength in heat-affected zones could be eliminated via grain refinement and anti-recrystallization effect during welding. Hot cracking in Al alloy welding could also be eliminated by the use of Sc modified filler material[8].

Sc is the 31st most abundant element with an average Earth crust which makes its rarity comparable with that of Co and Pb, even though it is infrequently found in moderate concentrations in naturally occurring minerals. Therefore, major Sc production today is provided via by-products of Ti, U, REEs, Ni and bauxite residue and the estimated production of Sc_2O_3 reaches 15tonnes/year[9-15]. Another important source for recycling could be the end life products containing Sc, especially Al-Sc alloys. Nevertheless, there is currently no reported recycling of these materials industrially[16,17] and limited amount of studies presenting feasible recycling routes[17,18]. Therefore, a complete and sustainable route for Sc recovery from Al-Sc alloys, Scalmalloy in this case, was proposed through hydrometallurgical methods in this study.

Conventional leaching of electronegative metallic particles and alloys with a strong mineral acid can result in generation of H_2 gas and an aggressive exothermic reaction. While such a leach process can be made safe at laboratory scale there are significant challenges at commercial scale from a control and zero harm perspective. Thus, an innovative leaching approach was applied with a metal salt solution of higher reduction potential to dissolve the metallic powders with cementation of the more electropositive metal from the leaching solution. Sc was then separated and purified from the impurities by solvent extraction. The end product, ScF_3, is another advantage of the solvent extraction process since it can be directly implemented into Al-Sc alloy or metallic Sc production through molten salt reduction. The process has also scaled up and tested in a continuous mini-pilot scale.

Results and Discussion

The Scalmalloy® material is designed to be processed using Laser Powder Bed Additive Layer Manufacturing (ALM) processes. Due to the high cooling rates and rapid solidification, a unique microstructure is achieved which rivals the performance of the highest-grade aluminium foundry products. Coupling these material properties with the design freedom provided by ALM processes can enable high performance parts with a level of functionality previously impossible to achieve. The Scalmalloy metallic powder is contains aluminium, magnesium, manganese, scandium, and zirconium. The starting material has a particle size of 10 to 120 μm. The elemental composition of a Scalmalloy powder is presented in Table 1.

Table 1. Elemental composition of Scalmalloy fine powder

SCALMALLOY® fine powder concentration in g/kg			
Al	930	Mn	5
Mg	48	Sc	7
		Zr	4

The fine particle size of the alloy powder makes it hard to process via pyrometallurgical operations although it is more common to process metallic wastes via re-smelting or re-fusing. Additionally, low impurities with high Sc amount in the alloy makes this waste a promising source for Sc. Hydrometallurgical operations were found to be the best option to process this alloy powder as they could separate Sc with high purity while consuming less energy compared to the pyrometallurgical options.

Nevertheless, when a conventional mineral acid is utilized to leach this alloy powder, an uncontrollable reaction occurs. Significant H_2 evolution was observed when metallic particles reacted with strong mineral acids and these acids have a higher reduction potential and propensity to yield hydrogen gas with its capacity to form explosive mixtures with oxygen. Moreover, this intense exothermic reaction makes temperature control extremely difficult. Even though almost complete dissolution of the constituent metals was observed employing conventional mineral acids, the reaction was unmanageable. Therefore, it was necessary to plan a new strategy to leach the elements from this alloy powder.

For this purpose, $CuSO_4$ solution was used as the lixiviant which yielded the following reactions upon addition:

$$2\ Me + 3\ Cu^{2+} = 2\ Me^{3+} + 3\ Cu(s)\ (Me = Al, Sc)$$
$$Me + Cu^{2+} = Me^{2+} + Cu(s)\ (Me = Mg, Mn)$$
$$Me + 2\ Cu^{2+} = Me^{4+} + 2\ Cu(s)\ (Me = Zr)$$

In this case, the elements in the metallic powder reacted with Cu^{+2} instead of H^+ (providing there was a stoichiometric excess of Cu 2+), in which Cu2+ is reduced into Cu(s) and the metallic constituents of the alloy are oxidized and dissolved in the aqueous solution. Thus, the reaction evolved into a controllable non-violent reaction where Cu(s) is obtained as the product while dissolving the alloy powder. Moreover, it is also possible to recycle the metallic Cu product via dissolving in sulfuric acid to reuse it as the lixiviant, which makes this process a sustainable alternative for alloy recovery.

Stoichiometric amount of $CuSO_4.5H_2O$ was reacted with the 9.5g of Scalmalloy alloy powder to verify the effectiveness of the leaching strategy. Leaching temperature was determined as 90ºC. Immediate formation of metallic Cu was observed upon addition of the Scalmalloy powder which indicated the successful reaction. The leaching efficiencies of the process were given in Table 2.

Table 2. Leaching efficiencies of the metals in Scalmalloy powder with $CuSO_4$ solution at 90ºC for 10 and 60 minutes

Duration	Al (%)	Sc (%)	Zr (%)	Mg (%)	Mn (%)
10 minutes	97.7	88.8	89.1	4.8	18.2
60 minutes	100	96.4	94.7	5.2	19.1

As can be seen from the Table 2, successful dissolution of the target elements was achieved. In addition, Mg and Mn leaching stayed at lower levels while almost all of Sc, Zr and Al was dissolved. After 1-hour processing duration, leaching efficiencies of 100%, 96.4 % and 94.7% were obtained for Al, Sc and Zr, respectively.

The PLS obtained was further processed with solvent extraction to isolate Sc from the impurities in the solution. For this purpose, 10 vol.% D2EHPA in D80 kerosene was selected as the extractant. Almost complete Sc extraction was observed in the extraction stage, while half of the Zr and minor amount of Al is co-extracted together with Sc. The extraction of Mg and Mn was found to be negligible. After extraction, the co-extracted impurities were scrubbed with H_2SO_4. Finally, the scrubbed organic was mixed with NH_4F in order to strip the extracted Sc from the organic and produce $(NH_4)_3ScF_6$ strip liquor. Table 3 shows the extraction, scrubbing and stripping efficiencies of the process.

Table 3. Extraction, scrubbing and stripping efficiencies of the solvent extraction process

Stage	Al (%)	Sc (%)	Zr (%)	Mg (%)	Mn (%)
Extraction	< 1	98.9	56.3	< 1	< 1
Scrubbing	66.5	< 1	36.3	99	99
Stripping	70.3	99.1	90.9	< 1	< 1

Sc is isolated from Al, Mg and Mn in the solution while some inclusion of the Zr occurs in the strip liquor. Process was found to be very promising to separate and purify electronegative metals from the alloys via hydrometallurgical operations. The continuous process flow diagram is presented in Figure 1. In the flowsheet below shows cemented Cu dissolution in sulfuric acid to provide a recyclable copper sulfate.

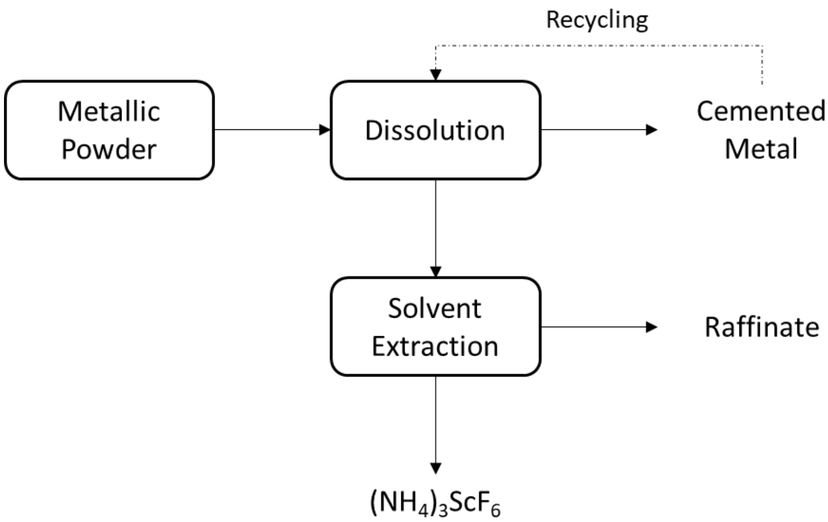

Figure 1. Basic flow diagram of the dissolution and solvent extraction process

Conclusions

We have thus demonstrated a process that is both quantitative and safe to treat extremely electronegative metals in a Scalmalloy alloy powder employing a hydrometallurgical process. In the first part of the process, alloy metal powder was successfully dissolved while eliminating problems associated with hydrogen gas generation when conventional mineral acids are employed. A more electropositive metal (Cu^{2+}) to hydrogen was employed in the dissolution process and furthermore this copper was recyclable thus adding to the sustainability of this leach process. In the second part of the process, Sc was almost completely recovered and isolated from most of the impurities. This strategy could also be applied in urban mining from electronic wastes. FeNdB magnets from the storage devices and metallic parts of the circuit boards are some candidate materials that could be utilized in this continuous process.

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