# RECYCLING OF COMPOSITE METALLIC COATINGS

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*Relevant topics: (1) Emerging Recovery & Recycling Technologies; (2) Innovative Remanufacturing Technologies*

## Abstract

Recycling of bimetallic composite coatings presents challenging opportunities as both the alloy substrates and coatings contain valuable resources for recovery and reuse. Several composite bimetallic layers have been investigated and their separation processes optimized. Four such combinations have been investigated, which include tantalum coated high temperature steel substrate, niobium coated tool steel, tin coated iron, and nichrome coated stainless steel. Various combinations of pyrometallurgical and hydrometallurgical techniques have been successfully applied to separate the composite layers. Optimized process conditions shall be presented for tantalum coated steel and tin coated iron.

This paper also summarizes various methods to recover tantalum from different secondary sources like tantalum capacitors, tantalum mill products, and tantalum in the chemical processing industry. Tantalum is a refractory metal with a low recycling rate of less than 1% because most tantalum secondary recovery techniques are primarily meant for recovery of other elements. The main factor for selecting the best recovery method is dependent on the materials which are mechanically or chemically bonded with tantalum. The best method to recover tantalum from tantalum coated steel has been discussed. Similarly, a key secondary resource for metallic tin is tinplated cans, which account for 25% of the domestic apparent consumption of tin. The recovery processes for recovering tin from tinplated metal cans are primarily electrochemical (electroplating and electrowinning) and chemical (leaching) techniques. In this study, one-step electrolytic detinning and two-step leaching and electrowinning processes for tin extraction in alkaline based solvents are reviewed and optimized for several process parameters. The anodic polarization behavior of pure bulk tin and tinplated steel anodes is studied for its active-passive characteristics in various alkaline based medium in the presence of oxidizing and reducing agents, and polarization parameters are summarized. Additives like potassium iodate as an oxidizing agent increases the tin dissolution rate and metallic aluminum additive as a reducing agent increases the electrodeposition rate in sodium hydroxide based medium.

## Introduction and Motivation

Bimetallic composites are metal-based coatings deposited on metal-based substrates using metal bonding techniques to improve the properties and performance of the composite material. According to Fact. MR report [1], the metal coating market in 2022 was estimated at 15.3 billion USD, and it is projected to increase by CAGR 6.9% by the year 2032 to 30.8 billion USD. Bimetallic composites are regularly used in critical industries like aerospace, chemical, automotive, electronic, and structural industries, where there is a critical need to protect materials from extreme service conditions and provide improved mechanical, thermal, wear and corrosion resistant properties. At their end-of-life or when damaged, bimetallic composites provide an important secondary resource for metals, especially critical and strategic metals, which is essential to support the supply chain, promote circular economy, and sustainability. Moreover, extraction of metals from secondary sources is more environmentally friendly than from virgin ores [2].

When compared to polymer or paint coatings, metal coatings are deposited by metal bonding techniques like cladding, welding, and cold spray techniques which join the metal using heat and plastic deformation, thereby chemically bonding the metals. It is challenging to recover such chemically bonded materials especially when it has undergone alloying and intermetallic phase formation at the interface. Another important factor is that the coatings are closely associated with a substrate and when it is desired to reuse the substrate then it is essential to remove the coating without adversely affecting the substrate. So, selection of the coating removal process is essential in such circumstances. Coating removal methods can broadly be classified into 5 methods – mechanical, physical, pyrometallurgy, hydrometallurgy, and electrometallurgy. Mechanical methods are a combination of several unit processes like

crushing, sieving, magnetic separation, eddy current separation, and density separation techniques, which are frequently applied to end-of-life materials, but they can result in loss of low concentration critical metals. Physical processes include impaction with abrasive materials or high-pressure water jet, which are efficient at thin coating removal but may damage the substrate. Hydrometallurgy includes methods like leaching and solvent extraction, and the use of such processes can produce significant waste solvents. Pyrometallurgical methods include roasting, pyrolysis, gasification, and laser ablation. Electrometallurgy methods include electrowinning and electroplating. The selection of the process depends on the material of coating and substrate, interfacial phase, and the end goal of the removal process. When the substrate is reusable, the coating must be removed without affecting the properties of the substrate. If the bimetallic composite is at its end-of-life, then it is desirable to valorize as best as possible. In this study, the aim is to investigate and discuss the four bimetallic composites for their coating removal and recycling techniques. Amongst these 4 composites, two coated systems of tantalum coated steel and tin coated steel are discussed in greater detail with experimental findings and process optimized parameters.

## Review of Related Work

### 1. Tantalum-coated steel

Tantalum is a refractory metal with a high melting point of 3017°C, corrosion resistant to most chemicals except for hydrofluoric acid, good mechanical strength, ductility, electrical conductivity, and biocompatibility. These properties make it desirable for many applications. In capacitors, tantalum is present as metallic anode and tantalum pentoxide dielectric material. Tantalum is found in mill products as pure or alloyed form like 90Ta-10W alloy. Tantalum recycling rate is less than 1% from waste printed circuit boards (PCBs) which account for 34% of total tantalum consumption [3]. Mechanical processes are not suitable with low concentrated tantalum containing products like tantalum capacitors, because such processes target precious elements and copper in waster PCBs, and tantalum gets lost due to low concentration [4]. Physical processes of impaction using abrasive media can be used to remove thin tantalum coatings. Methods like roasting and high-temperature oxidation use oxygen to recover tantalum pentoxide from capacitor scrap and tantalum coated steels [4, 5]. Pyrolysis and chloride metallurgy yields tantalum in the form of metallic tantalum and $TaCl_5$ [6, 7]. Pyrometallurgical techniques are more popular for tantalum extraction than hydrometallurgical methods because tantalum is resistant to most acids except for hydrofluoric acid and concentrated acids can reduce the value of recovered substrate materials.

### 2. Niobium-coated steel

Niobium is a refractory metal with chemical properties very similar to tantalum. Niobium is coated onto steel by thermal spray processes, cold spray technology, and cladding methods, and it is used in chemical processing industries, aerospace, and defense industries. Niobium is a very resistant metal which presents challenges in its selective extraction from steel using common techniques like mechanical, impaction, and leaching techniques. Niobium metal is very hard to electroplate selectively because it readily forms a protective oxide layer. Niobium can be electroplated from molten salts, but it requires high temperatures and energy consumption. Niobium readily oxidizes to stable higher oxidative states ranging from +1 to +5. Due to this property, selective oxidation of niobium coating by varying parameters of temperature, time and oxygen pressure, niobium pentoxide (thermodynamically most stable phase) can be recovered [8, 9].

### 3. Tin-coated steel

Tin coated steel or tinplated steel finds applications in canning industry, domestic appliances, toys, and electronics. Tin is coated onto steel by hot or cold rolling, dip coating, or electroplating processes. The thickness of tin coating varies between 0.1 to 0.3mm which is less than 1wt.% of the overall thickness of tinplated steel. Tin coated steel can be recycled by diluting with primary steel, but this is a steel upgrading process where tin is lost. Tin coating is most commonly removed using electrochemical processes including electroplating and electrowinning which is also the process for primary tinplated steel manufacturing [10, 11, 12, 13, 14].

### 4. CrC-Nichrome coated steel

CrC-Nichrome are cermet coatings with heat and corrosion resistant properties up to 900°C which makes it suitable for use as a coating in elevated temperature environments like in aerospace industries. Generally, thermal spray coatings can be removed by methods like impact blasting with sand, grit, $CO_2$, high-pressure water jet, or laser ablation [15, 16]. These methods are particularly applicable when the coating is thin. For thicker coatings, secondary steelmaking by diluting / blending with other scrap or primary steel is a suitable method because the composition of coating is similar to frequently used alloying elements for steel.

## Technology Approach

The initial sample characteristics of each bimetallic composite are summarized in Table 1. Each bimetallic composite differs from each other, especially in terms of coating thickness, coating composition, interfacial characteristics, and grade of steel substrate. It is critical to understand the physical and chemical properties of the coating and substrate, and the thermodynamic properties of the coated system, in order to choose an efficient and appropriate coating removal method. Tantalum and niobium are refractory metals which have high affinity for oxygen and readily oxidize above temperatures of 400°C to form thermodynamically stable phases of tantalum pentoxide ($Ta_2O_5$) and niobium pentoxide ($Nb_2O_5$) [17, 18]. These oxide phases find a variety of applications making them value added materials when recovered selectively from steel substrates. Figure 1 (a) shows the Gibbs free energy diagram for formation of stable oxide phases for Ta, Nb, Cr, and Fe. $Ta_2O_5$ and $Nb_2O_5$ are most thermodynamically stable phases in a closely associated system with steel (Fe, Cr). In the present study, high-temperature oxidation parameters of temperature and time were evaluated for selective removal of Ta and Nb as stable oxide powders.

On the other hand, metallic tin is a commercially and commonly electroplatable metal due to its high standard electrode potential, wide operating potential window, and tendency to form a smooth finish. Figure 1 (b) shows Pourbaix diagram for Sn-Fe-$H_2O$ system at 298K. Tin readily forms stannate and stannite ions and goes into solution in acidic and alkaline mediums. In association with iron or steel substrate, selective electroplating of tin is preferred from alkaline electrolytes to avoid corrosion of steel substrate.

Lastly, cermet coatings like CrC embedded in nichrome matrix is commonly removed using impacting techniques like abrasive media blasting or high pressure water jet. In this study, we evaluated the secondary steelmaking process for recycling of CrC-nichrome coated stainless steel composite because of commonly used steel alloying elements in the coating, i.e., Cr and Ni. Table 2 summarizes the adopted coating removal techniques and resulting products for each of the bimetallic composite considered in the present study.

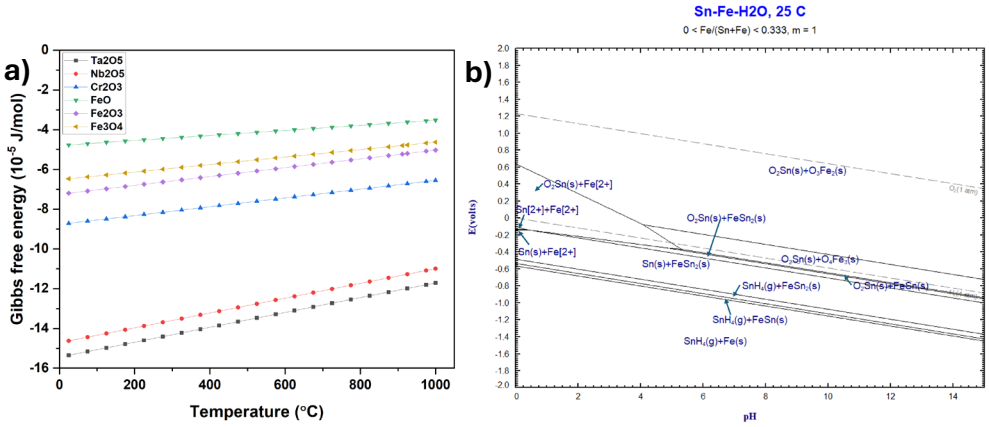


Figure 1. a) Gibbs free energy of formation of oxides of Ta, Nb, Cr, and Fe. b) Pourbaix diagram of Sn-Fe-H2O system.

Table 1. Initial material characterization of four bimetallic composites.

| Bimetallic composite | | Deposition process | Coating thickness ($\mu m$) | Interdiffusion interface thickness ($\mu m$) | Intermetallic phase |
|---|---|---|---|---|---|
| **Tantalum coated steel** | Tantalum-coated 4130 steel (sample 1) | Cold-spray | 516 | 1-3 | $Fe_{0.975}Ta_{0.025}$ |
| | Tantalum-coated A36 steel (sample 2) | | 625 | 5 | $Fe_{0.975}Ta_{0.025}$ |
| | Tantalum-coated low-carbon steel (sample 3) | | 4000 | - | $Fe_{0.975}Ta_{0.025}$ |
| | Tantalum-coated medium-carbon steel (sample 4) | | 8000 | - | $Fe_{0.975}Ta_{0.025}$ |
| Niobium coated type 440C tool steel | | Cold-spray | 106.5 | - | - |
| Tinplated steel | | Dip-coating | 2.6 | 0.7 | $FeSn_2$ |
| CrC-Nichrome coated 316 stainless steel | | Cold-spray | 2500 | - | - |

Table 2. Summary of coating removal processes adopted for each bimetallic composite.

| Bimetallic composite | Removal process | Influencing parameters | Product |
|---|---|---|---|
| Tantalum coated steel | High-temperature oxidation | Temperature and time | $Ta_2O_5$ and un-coated steel |
| Niobium coated steel | High-temperature oxidation | Temperature and time | $Nb_2O_5$ and un-coated steel |
| Tin coated steel | 1. Electrolytic detinning | Electrolyte composition, current density, time, temperature, pH, lixiviant composition | Tin and un-coated steel |
| | 2. Alkaline leaching and Electrowinning | | |
| CrC-Nichrome coated steel | Secondary steelmaking by blending with scrap and virgin steel | Presence and composition of flux, temperature, and reaction time | Secondary steel |

## Results and discussion

### 1. Recovery of tantalum and niobium coatings using high temperature oxidation

In the present study, thermogravimetric analysis (TGA) was first conducted to understand the influence of temperature on oxidation behaviors of pure Ta and Nb. Subsequently, discontinuous oxidation study is carried out in muffle furnace on the whole coated composite to understand the influence of oxidation parameters on oxidation behavior of composite and resulting products

#### 1.1. Thermogravimetric analysis

Figure 2 shows the isothermal TGA analysis of pure tantalum film and niobium coating. Under 400°C, tantalum forms amorphous suboxides consisting of orthorhombic and tetragonal phases of tantalum suboxides and follows a slow logarithmic rate of oxidation, as shown in Figure 2 (a). Between 500-800°C, tantalum oxidation follows fast linear kinetics. Niobium coating follows two-stage linear oxidation kinetics above 500°C, as shown in Figure 2 (b). The second stage of niobium oxidation follows fast linear kinetics as a result of breakaway oxidation. Both $Ta_2O_5$ and $Nb_2O_5$ oxides have a high Pilling-Bedworth ratio of 2.47 and 2.69, respectively. This implies that these oxides undergo stress cracking due to high compressive stress build-up from short-circuit diffusion of oxygen through the oxide lattice. This results in chilling and spallation of these metal oxides resulting in rapid oxidation. The optimal oxidation temperature for Ta and Nb were determined to be 700°C and 500°C, respectively. These temperatures are the lowest temperatures required for formation of tantalum and niobium pentoxides without significantly degrading the steel.

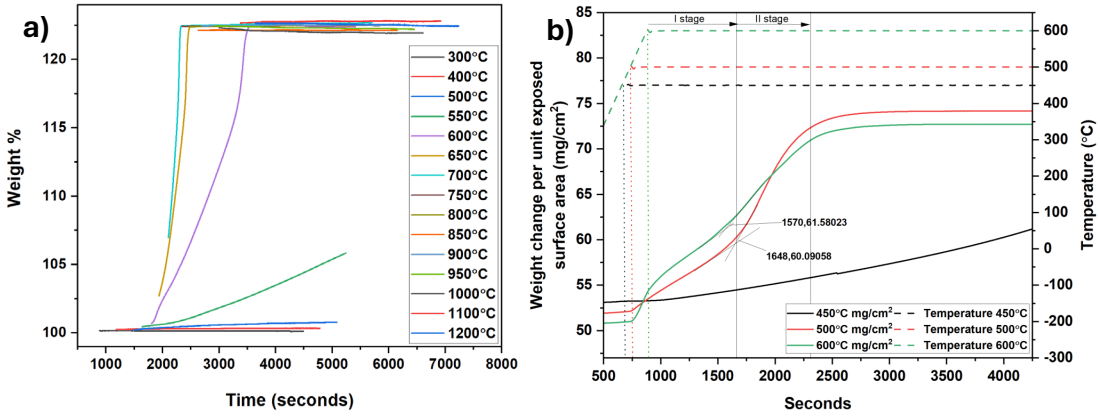


Figure 2. Isothermal TGA analysis of a) pure tantalum thin film, and b) niobium coating.

#### 1.2. Discontinuous oxidation

Discontinuous oxidation tests of Nb and Ta coated composites were studied in a muffle furnace in air atmosphere. The weight gain per unit exposed surface area of niobium coated type 440C tool steel is shown in Figure 3. The oxidation kinetics were determined using Arrhenius equation and activation energy for niobium coated steel composite is 20J/mol. Table 3 summarizes the oxidation kinetic summary for the four different samples of tantalum coated steels. The overall kinetics of coated composite are heavily influenced by the grade of steel. Carbon steel substrates are more susceptible to corrosion at higher temperatures, which leads to the formation of chromium and aluminum oxide that can contaminate tantalum pentoxide products and reduce the reusability of steel. Based on the test results, the

activation energies are lower for the thinner coating samples of tantalum coated 4130 steel and tantalum coated A36 steel compared to the tantalum coated carbon steels, because thicker coatings require more time to fully oxidize.

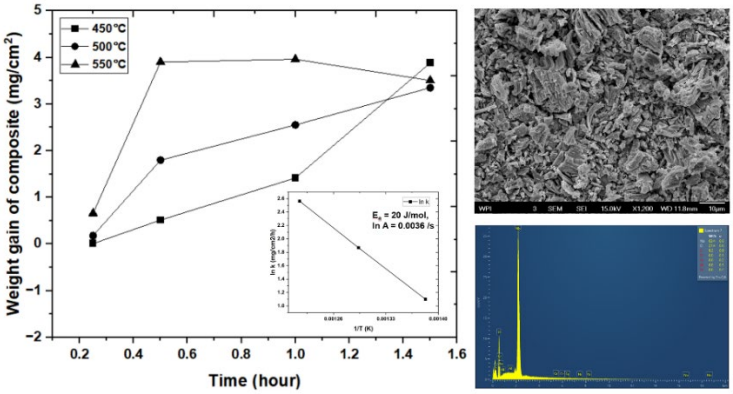


Figure 3. Discontinuous oxidation of niobium coated 440C tool steel. a) Weight gain per unit exposed surface area vs time, and corresponding SEM-EDS micrographs.

Table 3. Oxidation kinetic parameters summary for tantalum coated steel composite.

| Sample | Temperature (°C) | Composite | | Steel substrate | |
|---|---|---|---|---|---|
| | | $E_a$ (kJ/mol) | A ($s^{-1}$) | $E_a$ (kJ/mol) | A ($s^{-1}$) |
| **Tantalum-coated 4130 steel** | 500-1000 | 78.54 | 98339 | 101.34 | 291032 |
| **Tantalum-coated A36 steel** | 550-750 | 34.86 | 327 | 41.31 | 89 |
| **Tantalum-coated low-carbon steel** | 700-900 | 99.58 | 389384 | 55.39 | 2564 |
| **Tantalum-coated medium-carbon steel** | 700-900 | 108.17 | 618591 | 97.36 | 88529 |

## 1.3. Post oxidation study of substrate for reusability

The post oxidation reusability of steel substrate was examined through elemental distribution near the coating-substrate boundaries. Tantalum in steel above a certain concentration can lead to brittleness. The diffusion of tantalum in steel is affected by oxidation parameters. Higher temperatures increase the mobility of atoms leading to faster diffusion rates. Tantalum diffuses faster in A36 steel than 4130 steel due to higher chromium content in 4130 steel. There was negligible diffusion of tantalum in the carbon steels due to incomplete oxidation of tantalum coating due to high thickness, but tantalum is expected to diffuse more in these steel substrates due to their lower tendencies to form protective passivation layers. The SEM-EDS results for tantalum coated 4130 steel and tantalum coated A36 steel are shown in Figure 4. The overlapping elemental line graphs represent phases of metal oxides and intermetallic compounds of Fe and Ta. In both the systems, the remainder of un-oxidized tantalum forms Fe-Ta phase at the interface. Moreover, at temperatures as low as 700°C, iron oxides are observed at the interface. Table 4 summarizes the SEM-EDS results for tantalum coated carbon steels. With steel substrates of low carbon and medium carbon steels, tantalum diffusion in these steel substrates is significantly higher than in the A36 and 4130 steel. This is attributed to thicker tantalum coatings and higher susceptibility to corrosion of carbon steels as a result of its chemical composition.

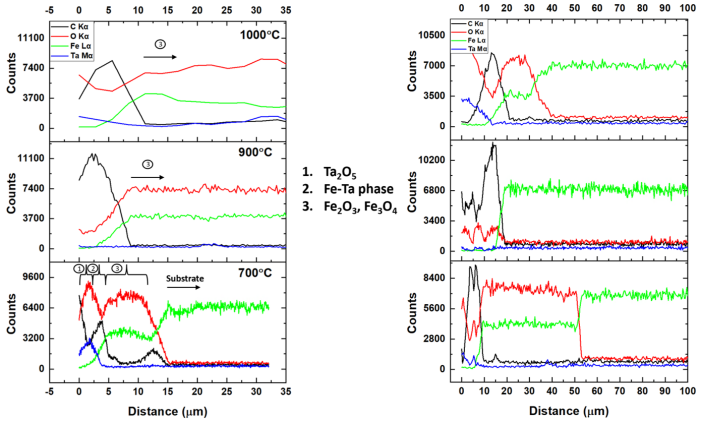

Figure 4. EDX line diagram of coating-substrate interface after high-temperature oxidation at 700°C, 900°C, and 1000°C for a) Tantalum coated 4130 steel, and b) Tantalum coated A36 steel.

Table 4. EDX results for elemental concentrations post oxidation

| **Tantalum coated low carbon steel (wt. %)** | **Ta** | **Fe** | **Cr** | **O** | **C** | **Mn** | **Mo** |
|---|---|---|---|---|---|---|---|
| Coating initial - overall | 96.0 | 0.1 | 0.0 | 1.1 | 2.6 | 0.0 | 0.1 |
| Coating initial (close to interface) | 96.0 | 0.0 | 0.0 | 1.1 | 2.5 | 0.0 | 0.3 |
| Substrate initial - overall | 0.5 | 92.5 | 0.2 | 0.8 | 3.0 | 2.8 | 0.1 |
| Substrate initial (close to interface) | 0.2 | 91.8 | 1.5 | 0.6 | 2.7 | 2.6 | 0.6 |
| **Tantalum coated medium carbon steel (wt. %)** | **Ta** | **Fe** | **Cr** | **O** | **C** | **Mn** | **Mo** |
| Coating initial - overall | 96.2 | 0.0 | 0.0 | 1.0 | 2.7 | 0.0 | 0.0 |
| Coating initial (close to interface) | 92.9 | 0.6 | 0.0 | 1.0 | 5.4 | 0.0 | 0.1 |
| Substrate initial (close to interface) | 1.2 | 90.0 | 4.7 | 0.1 | 2.8 | 0.0 | 0.0 |

For post-oxidized niobium coated type 440C tool steel samples, Figure 5 shows EDX elemental mapping micrographs across a cross-section. At lower temperatures of 450°C and 500°C, the steel substrate preserves the pre-existing chromia and alumina scales in the samples before oxidation. At 550°C, iron and chromia scale detachment was observed. At all conditions, a discontinuous thin scale of alumina was observed.

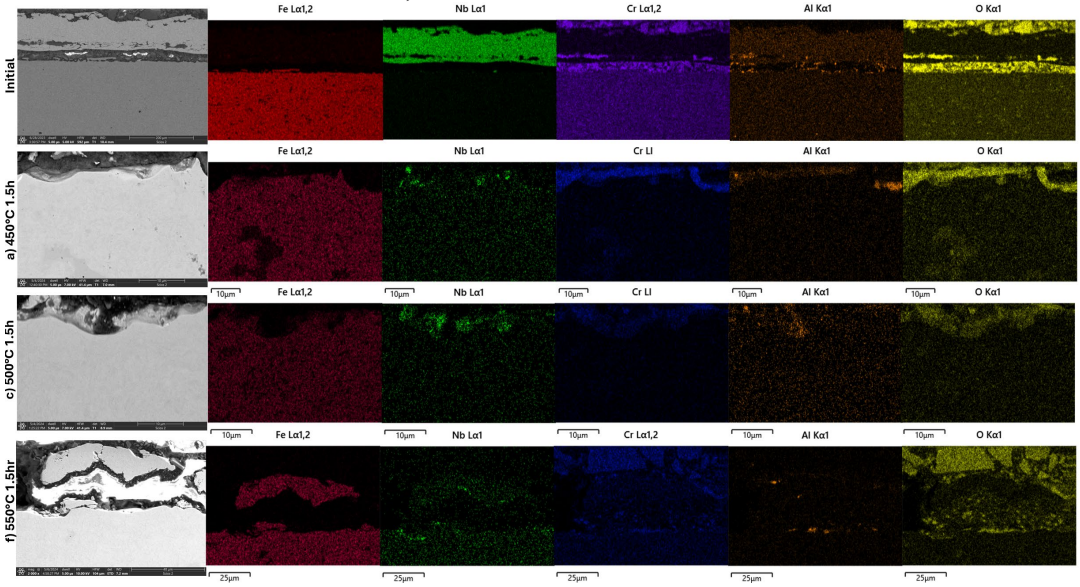


Figure 5. EDX elemental mapping of 440C tool steel substrate after oxidation to remove niobium coating

## 2. Electrochemical recovery of tinplated steel

Tinplated steel recycling is carried out using two electrochemical processes – 1) one-step electrolytic detinning, and 2) two-step leaching and electrowinning process. First, anodic polarization behavior tinplated steel is tested in different electrolytes to understand the active-passive behavior of tinplated steel. Subsequently, lab-scale experiments are conducted to evaluate and optimize process parameters for electrochemical recovery of tinplated steel.

### 2.1. Anodic polarization behavior

Anodic polarization behavior of tinplated steel anode was studied with varying electrolyte concentrations as shown in Figure 6. In purely alkaline medium of NaOH and KOH, tin-plated steel exhibits active-passive behavior. In KOH medium, the critical current density is higher than that in NaOH medium indicating higher dissolution kinetics due to greater basicity of KOH. With the addition of $KIO_3$, an oxidizing agent, the anodic polarization behavior changes drastically. In the presence of oxidizing agent, the passivation tendency of the anode increases. The current density sharply decreases before passivation in KOH + $KIO_3$ mixture, compared to immediate passivation following active anode dissolution in NaOH + $KIO_3$ mixture. This implies that a uniform passivating film forms in NaOH based medium, and in KOH medium the passivating film is formed abruptly due to possible changes in surface conditions. Moreover, in KOH + $KIO_3$ mixture, the transpassive characteristics of anode increases with current density and potential, indicating pitting or crevice corrosion due to the oxide layer breakdown. In NaOH + $KIO_3$ mixture, the oxide film is more stable and adherent because the current density increases gradually with increase in potential. In the

presence of reducing agent of aluminum, the polarization behavior of tinplated anode is similar to that of NaOH and $KIO_3$ mixture.

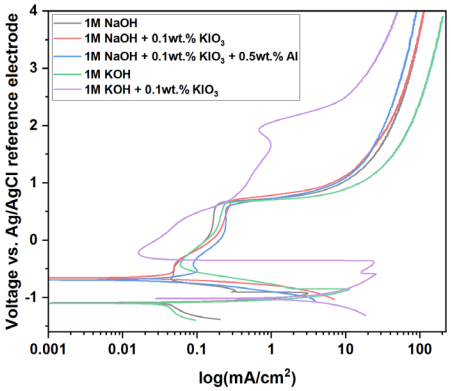


Figure 6. Anodic polarization behavior of tinplated steel anode.

## 2.2. One-step electrolytic detinning

In a one-step electrolytic detinning process, under the driving force of electrode potential difference, tin is selectively deposited on a cathode surface using constant current or constant potential difference between tinplated steel anode and a suitable cathode immersed in an alkaline electrolyte solution. The influential process parameters are electrolyte composition and concentration, oxidizing agent, temperature, time, doping agent and current density. Figure 7 shows the results for electrolytic detinning under different conditions. The optimal conditions for electrolytic detinning are electrolyte mixture of 2M NaOH and 25g/l $Na_sSnO_3$ at 100A/m$^2$ current density. The process parameters are strongly influenced by the thickness of tin coating, presence of intermetallic $FeSn_2$ phase, and reversible reaction of Sn(II) to Sn(III) which influences the deposition characteristics. After the depletion of the outer metallic tin coating, $FeSn_2$ intermetallic phase acts as an anode facilitating the fast dissolution of tin from this phase [19]. When tin dissolves primarily as stannate ions ($HSnO_2^-$), cathode deposit is spongey tin which is easy to dislodge, and current efficiency is higher. Predominance of stannite ions ($SnO_3^{2-}$) leads to adherent cathodic deposit, and lower current efficiency because more electricity is required for two step reduction from $Sn^{4+}$ to Sn.

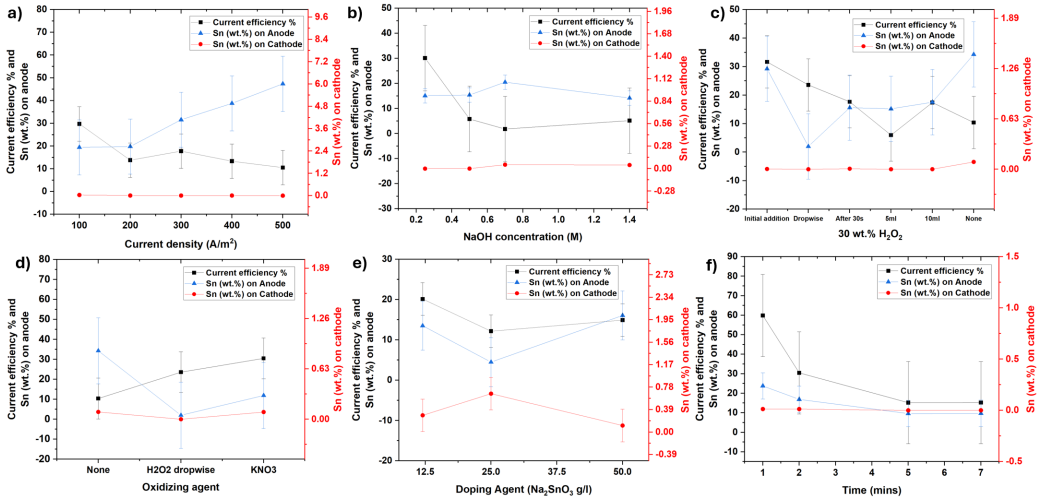


Figure 7. Electrolytic detinning process parameters for tinplated steel dissolution. Effect of a) current density, b) NaOH concentration, c) $H_2O_2$ addition, d) oxidizing agents, e) doping agent, and f) time.

## 2.3. Two-step leaching and electrowinning

In the two-step leaching and electrowinning process for tin recovery, tin is first oxidized and dissolved in an alkaline based lixiviant, which is subsequently used for electrowinning of tin ions on a cathode surface. The leaching process is governed by chemical potential difference and electrowinning process is driven by electrode potential difference. Figure 8 shows the optimization of experimental results for leaching of tinplated steel. The optimal conditions for leaching are 0.5M KOH + 0.25M $KIO_3$, tin/lixiviant ratio of 25g/l, and 13.32pH. The dissolution kinetics did not

change significantly with the increase in temperature. Using the method of least square, the activation energy for leaching was calculated to be 7.1kJ/mol using flat plate approximation.

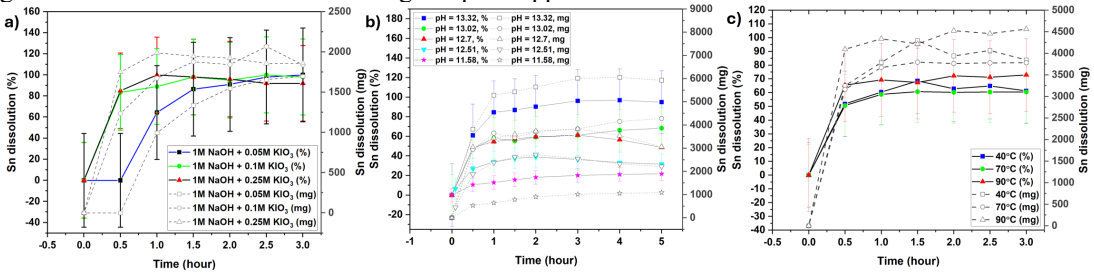


Figure 8. The leaching process parameters for tinplated steel. Effect of a) electrolyte composition, b) pH, and c) temperature on the leaching kinetics of tinplated steel.

Figure 9 shows the optimization of electrowinning parameters. Aluminum was used as a reducing agent because of its high reduction potential. The optimized electrowinning parameters are 0.5M KOH + 0.25M $KIO_3$, 2.5wt.% Al, at current density 500A/$m^2$ and 60C. Electrowinning parameters are also strongly influenced by cathode material. The electrodeposition rate was found to be higher for lead cathode due to the formation of Pb-Sn phase, and lower for copper cathode because it leads to oxidation to tin oxide.

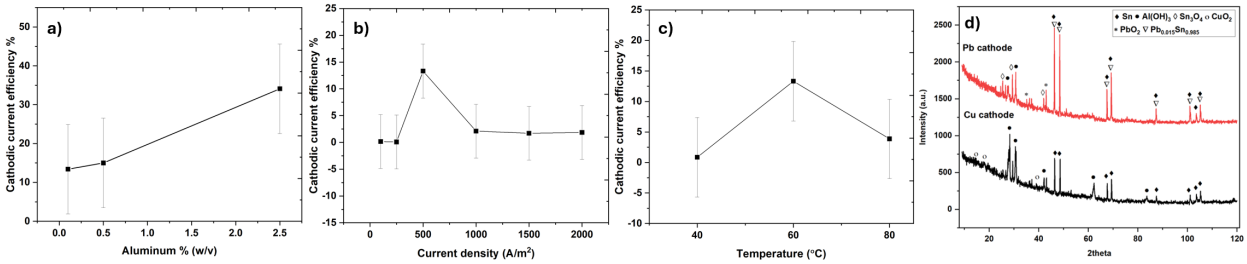


Figure 9. Electrowinning process parameter optimization. Effect of a) reducing agent addition, b) current density, and c) temperature. d) XRD analysis of cathode deposits to evaluate the effect of Pb and Cu cathode on electroplated tin retention.

## 3. Secondary steelmaking blending of CrC-Nichrome coated stainless steel

For recycling of CrC-nichrome coated 316 stainless steel, a secondary steelmaking route by blending with scrap steel was adopted in the study. The blending with scrap steel was determined preliminarily by developing an under-determined blending mathematical model based on linear programming. The blending model was used to determine the amount of different types of scrap steel with specified compositions to be mixed with CrC-nichrome coated 316 stainless steel composite for a resulting stainless steel. The blending experiments were conducted in a 25-40lb capacity induction furnace. The results of blending experiments are shown in Figure 10. The experiment 3 was carried out in the presence of a basic flux with basicity of $CaO/SiO_2$ of 4 (Run#3). All other experiments were conducted without flux. A high recovery rate was achieved for Cr and Ni for all runs except for the once with the usage of flux. The flux used was determined to be acidic for the recovery of Cr and Ni.

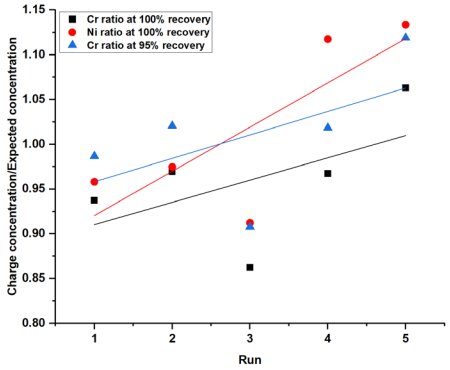

Figure 10. Ratio of Cr and Ni in charge concentration with respect to expected concentration using blending model.

## Conclusion & Recommendations

In conclusion, bimetallic composites are a valuable secondary resource for base, critical, and strategic metals. Bimetallic composite recycling can be broadly classified into mechanical (shredding, density separation, magnetic separation, etc.), physical (impacting technologies like abrasive media or water jet, ultrasonic separation), pyrometallurgy (roasting, oxidation, pyrolysis), hydrometallurgical, or electrometallurgical methods. The recycling and recovery process of the metal coating and substrate is dictated by the end application (refurbishment, inspection, or recycling), chemical and physical properties of coating and substrate, and interdiffusion interface. Four bimetallic composites were discussed in this study, and experimental optimization results were provided for tantalum coated steel and tinplated steel systems. High temperature oxidation process of tantalum coated steel and niobium coated type 440C tool steel yields value added materials of tantalum pentoxide, niobium pentoxide and respected reusable steel substrates. The oxidizing parameters are essential to be optimized for a particular tantalum coated steel system in order to prevent steel oxidation and maximize oxide recovery rate with minimal contamination from oxides of substrate. The most influential oxidizing parameters were determined to be coating thickness, grade of steel and its chemical makeup, temperature and time. In future studies, it would be recommended to study the effects of oxygen partial pressure and the post oxidation mechanical properties of steel substrate. One-step electrolytical detinning and two-step leaching & electrowinning of tin for separation from steel substrate was presented and optimized for several process parameters. The factors contributing to the cathodic electrodeposition rates are thickness of tin coating, intermetallic $FeSn_2$ phase, and reversible reaction of Sn(II) to Sn(IV). These parameters also influence the characteristics of the deposit. For future studies, it would be recommended to study the parameters influencing the presence of dominant tin ionic form in solution which affects the electrodeposition kinetics and characteristics of cathodic deposit. Lastly, secondary steelmaking from the blending of CrC-nichrome coated stainless steel with scrap steels was demonstrated as its potential recycling process which yields secondary stainless steel.

## Acknowledgements

The authors would like to acknowledge the Center for Resource, Recovery and Recycling ($CR^3$), and Materials Recovery Technology for Defense Supply Resiliency (MRT-DSR) program for sponsoring and supporting this project.

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