

An Overview of the Sustainable Production of Vanadium through Metallurgical Recycling of Slags

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Abstract

The vital uses of vanadium in metallurgy and the expansion of vanadium redox flow batteries (VRFB) as a commercial product have raised demand for vanadium. Thus, it is crucial to guarantee the long-term viability of vanadium production [1-15]. The main source of vanadium production is from solid byproducts of iron and steel manufacturing, or vanadium bearing slags, which account for more than 69 percent of all vanadium in terms of raw material types. Such metallurgical procedures for treating the The vital uses of vanadium in metallurgy and the expansion of vanadium redox flow batteries (VRFB) as a commercial product have raised demand for vanadium. Thus, it is crucial to guarantee the long-term viability of vanadium production. The main source of vanadium production is from solid byproducts of iron and steel manufacturing, or vanadium bearing slagshave been developed as a result of academic studies and engineering investigations. This article provides an in-depth analysis of metallurgical processes used on slags containing vanadium. Vanadium-bearing slags from various sources are described in terms of their composition, phases, and minerals. A survey of the literature reveals that the roasting-assisted leaching approach has traditionally been used to handle vanadium-bearing slags, despite current efforts to integrate cutting-edge technology in extractive metallurgy and create direct leaching techniques. Some attractive and worthwhile approaches are anticipated to constitute the area's future research priorities. The separation of vanadium from silica, phosphorus, and chromium is also highlighted in the discussion as the main interfering elements/metals in the leach solutions of vanadium slags. It is advised that additional research be conducted in the future to create a sustainable metallurgical method for vanadium-bearing slag.

Introduction

Vanadium is utilised in a variety of disciplines in contemporary industries, including steel manufacture (92.9%), non-ferrous alloys (4.0%), chemical production (3.0%), batteries (0.1%), and others (<https://roskill.com/market-report/vanadium/>). Since its first application in the Ford Model T, vanadium as an additive in the steel-making process has improved the tensile strength and toughness of the steels, and the products have been used for crankshaft, camshaft, connecting rods, differential spider, transmission shafts, axles, gears, valve springs, etc. in vehicles. Additionally, due of their exceptional strength and toughness, vanadium steels are utilised to create high-speed tool steels with o contents ranging from 1 percent to 5 percent. f vanadium and high-vanadium steel rebar, 0.03 percent to 0.1% V, which is in significant demand in the building industry One of the well-known materials used in fusion reactors is V-4Cr-4Ti, a non-ferrous alloy. Vanadium compounds play a significant role in the chemical industry since they are frequently utilised as a catalyst in the production of sulfuric acid and maleic acid [4]. This metal is specifically used in batteries as the active ingredient in liquid electrolytes (sulphate or bromide based) that filled the anodic (V²⁺/V³⁺) and cathodic (VO²⁺/VO²⁺) half-cells of a redox flow battery (referred to as a vanadium redox flow battery/VRFB) this is the only commercially available RFB at the time of writing.

According to since 2011, the world's vanadium consumption has grown by roughly 45 percent, reaching 102.1 kilotons in 2019. By the end of 2024, consumption is projected to increase by up to 130.1 kilotons at an annual growth rate of 5%, with the rise in demand for high strength steel serving as the primary driver of this increase.

One of the factors contributing to the projected increase in vanadium consumption is the growing use of VRFB as a supporting component of developing renewable energy installations in several nations. There is currently no substitute for vanadium that can be used in aircraft titanium alloys indicating the importance of this element in such crucial fields.

Subjective Heading

To ensure the sustainable production and supply of vanadium, it is crucial to comprehend the significant applications of the metal. Vanadium occurs naturally as oxides, sulphides, and phosphates in the forms of titanomagnetite, patronite, vanadinite, descloizite, and carnotite, which are linked to other metals such iron, titanium, lead, aluminium, zinc, and uranium .The primary source of vanadium among them is titanomagnetite/iron ores, which account for more than 88 percent of vanadium production.However, the vanadium grade is quite low for direct vanadium production; it is typically less than 1% and occasionally even lower in the processed .Actually, the ores are typically beneficiated first before being used as feed for direct reduction (DR) or blast furnaces.

Discussion

Vanadium is mostly extracted from these slags by a roasting-assisted leaching process, followed by separation/purification and recovery processes through precipitation to obtain products of vanadium metal, vanadium pentoxide, ferrovanadium, or other compounds. Several research works dedicated to developing such

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processes to extract vanadium out of vanadium bearing slags have been published. Recently, certain adjustments to the traditional roasting and leaching procedures have been made, along with attempts to construct entire downstream hydrometallurgical systems.

The treatment of vanadium-bearing slag and the subsequent metal separation from the leach solution of vanadium-bearing slag have not been the topic of any reviews addressing the extractive metallurgy of vanadium studies. Vanadium extraction from titanomagnetites and other sources was recently reviewed by Gallagan and Nikoloski however specifics on the handling of vanadium-bearing slags were only briefly mentioned. Additionally, it was not precisely stated what new and recent advancements had been made in the extraction and treatment processes, particularly for the separation of vanadium from its rival components and metals. Consequently, the current review made to analyze and compile the metallurgical treatments of vanadium bearing slags while focusing the discussion relating to the respective treatments based on the scientific interpretations especially the thermodynamics and chemistry's foundational principles. In order to present a comprehensive overview of the state of the art metallurgical treatments of vanadium bearing slags, the state-of-the-art methods in this sector are also covered. To shed light on the choice of such procedures for removing vanadium from slags, evaluations of the economic and environmental aspects of the corresponding processes are provided. In particular, the extraction and separation of vanadium are the main topics of debate, with chromium being the principal metal to interfere throughout this process.

explains the chemical make-up and phases of vanadium-bearing slags produced by various iron- and steel-making facilities. CaO, SiO₂, MgO, and Al₂O₃ concentrations in vanadium-bearing slags typically vary from 2 to 45 percent, 6 to 25 percent, 1 to 16 percent, and 2 to 10 percent, respectively. Vanadium oxides' chemical compositions—as V₂O₃ or V₂O₅—vary based on the different inputs charged into the furnaces, the effectiveness of such operations, and the intended end products. Due to similar factors, chromium oxide is also found in the vanadium bearing slags. Chromium particularly interferes with the vanadium extraction process, implies that subsequent metal separation after vanadium extraction is critical to obtain vanadium of high purity. Titanium oxide in the titanomagnetite ore is hardly reduced and mostly transferred to the slag during reduction smelting. Even so, a small portion of titanium is often found in the molten metal and further removed together with vanadium in the oxygen blowing practice.

Following the order: Cr-spinel > V-spinel > Ti-spinel based on the difference in each spinel's capacity to crystallise. Manganese, for example, is evenly distributed throughout the spinel grain. Magnesium is concentrated in MgCr₂O₄ with chromium acting as the minor phase. Due to the large dosage of limestone used during the production of iron and steel, the other vanadium phase of Ca₂V₂O₇ was also discovered are also recognised other oxides that come from the fluxes applied to the furnaces. The input materials, production rates, and technological advancements used during the iron/steel-making process all affect the vanadium level of the slags. Even so, commercial vanadium slag production facilities, including those at Highveld Steel and Vanadium Corp. in South Africa, Chengde Iron and Steel Group in China, Nizhny Tagil Iron and Steel Works in Russia, etc., use a number of common features, most notably the use of sodium salt roasting-water leaching-ammonia precipitation. A typical flowsheet used in commercial plants, specifically the one used at Chengde Iron and Steel Group as an example, is shown in Fig. 3 for the production of vanadium from slag. The vanadium-bearing slags are usually treated by leaching. The

Eh-pH graphs of vanadium and chromium, the two key metals in the vanadium carrying slags presented in Supplementary demonstrate the ease with which both acidic and alkaline solutions can attack the two metals. The low leaching yields make direct atmospheric leaching of vanadium-bearing slag using NaOH or H₂SO₄ solutions undesirable. Because roasting is currently the only economically successful approach for treating vanadium-containing slags, leaching is aided by roasting.

The purpose of roasting is to degrade the stable spinel phases by transforming them into leachable forms, allowing for easier attack during the subsequent leaching stage in water/H₂SO₄/alkaline. In order to achieve good roasting, a higher temperature should be maintained when employing sodium sulphate, regardless of whether the roasting is done without or with additions. The results of extensive experiments on the leaching of vanadium-bearing slag with roasting assistance are compiled.

Conclusion

Alternative roasting systems to the conventional sodium/calcium salt roasting technique have also been developed. Recently, MgO-based roasting was practised in a manner akin to calcification roasting. Vanadates like MgV₂O₆, Mg₂V₂O₇, and Mg₃V₂O₈ are formed as a result of the quicker diffusion rate of magnesium ions into the V-spinel and may then be leached out using sulfuric acid. After roasting at 900°C, Mg/V ratio = 0.6, roasting time of 1.5 h, and leaching using a solution with pH 0.5 at 70°C for 2 h, more than 90% of the vanadium was recovered. Vanadium and magnesium that had leached from the solution were separated by ammonia-adjusted pH-selective precipitation.

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Conflict of Interest

The authors declare that they are no conflict of interest.

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