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METALLURGY ON THE MOON: FUNDAMENTAL LIMITS

Abstract

The Artemis program and other international space programs are likely to lead to human habitation on the surface of Moon in the 2030s. In addition to providing a sustainable living environment, oxygen, food supply and energy, there is an expectation that metals and ceramic products will be produced from the available materials, that is regolith, metallic scrap on the lunar surface and chemical supplies from earth. This interest in metal production has led to various research programs over the last few decades looking at electrolytic, chemical reduction (notably carbon and hydrogen) and thermal reduction routes to metal production. Molten oxide electrolysis (MOE) remains favoured as a potential technique because it produces both oxygen and metal, and because the technology doesn't require a reductant. To date, there has been very little research on the subsequent refining and casting of metals on lunar surface, though recently these topics have been explored at Swinburne University of Technology.

In exploring these different options, chemical thermodynamics, fluid mechanics and heat transfer can be applied to define the limits of the process. In the case of lunar conditions, the effect of gravity and high vacuum can be incorporated into the analysis using fundamental physics. For example, the temperature required to thermally breakdown lunar regolith to metallic iron can be determined using chemical thermodynamic packages; similarly, how much oxygen is required to refine molten ferrosilicon to pure iron and how this affects the iron yield can calculated. For example, carbothermic reduction of lunar regolith simulant (LMS-1) enables the extraction of 100 grams of Fe-Si alloy (8-9 wt.% Si) from 1 kg of simulant using just 20 grams of carbon. This Fe-Si alloy (9 wt. %Si) can be further refined to Fe (1 wt. %Si) by directly injecting 11 grams of oxygen into the molten Fe-Si alloy at 1600 C. A detailed Ellingham diagram (Gibbs Free Energy vs. temperature) which show the relative stability of different oxide/metals has been constructed for the vacuum conditions on the moon and the repercussions of this diagram are profound to understand the potential of different routes. The lack of convective heat transfer during casting has also been calculated and demonstrates that radiative cooling is 100x slower than typical process cooling rates, which in turn will affect microstructure and properties. Detailed examples from thermal reduction of regolith to produce iron, refining and radiative cooling of iron silicon will be presented.