Rapid solid compound reduction by an atmospheric pressure hydrogen microwave plasma toward carbon-free production

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Abstract: Iron and steelmaking account for 7-9% of global CO_2 emissions. We report rapid in-flight metal oxide reduction using the atmospheric pressure hydrogen microwave plasma, which is more than 100 times faster than the previously reported "flash" in-flight iron ore reduction by thermal hydrogen. This technique shows the potential for reducing various metal oxides and the ability to synthesize nanometer-size metal alloys or compounds.

1. Introduction

The iron and steel making industry globally is the largest industrial emitter of CO_2, directly responsible for 2.6 Gt CO_2 emissions per year [1]. In the traditional blast furnace reduction (BFR), coke, refined coal, acts as an energy source and reducing agent, producing large amounts of CO_2. Direct reduction of iron ore (DRI) [2] has been developed as a lower-carbon alternative to BFR. However, most DRI processes use natural gas and are thus not fully carbon-free. Direct reduction using hydrogen gas can potentially achieve this goal if "green" hydrogen from electrolysis is used as a reductant. The in-flight reduction of iron ore particles by H_2, also known as flash iron making, has emerged as a promising technology. However, at the pilot plant scale, the approach still relies on the partial combustion of natural gas and hydrogen as a source of heat and reductant [3].

2. Methods

We used microwave argon-hydrogen plasma for the rapid reduction of various metal oxide powders. An argon-hydrogen gas mixture (90:10 volume %) entered the quartz tube from the top. To enable in-flight injection, the Ar:H_2 mixture flows through a particle feeder that contains metal oxide particles, which the gas flow carries into the system. The hydrogen plasma then in-flight reduces the particles, which are collected by a cotton filter far from the plasma.

3. Results and Discussion

Various metal oxide particles, Fe_3O_4, CuO, and NiO, and their mixture were sent through the plasma reactor for in-flight reduction. The hydrogen plasma reduced Fe_3O_4 particles in-flight, resulting in metallic iron nanoparticles collected by the filter. The particles exhibited a velocity of roughly 3.5 m/s during reduction, implying that a Fe_3O_4 particle passing through the hydrogen plasma had a residence time of only around 40 ms. This is over 100 times faster than the previously reported "flash" in-flight iron ore reduction by thermal hydrogen [4]. The XRD patterns in Fig. 1 also indicate that CuO particles were fully reduced to metallic Cu. When feeding a CuO-Fe_3O_4 particle mixture to the reactor, XRD shows a shoulder on the Cu peak, which indicates an Fe-Cu alloy. NiO has a much higher melting temperature, thus, in Fig. 1, in-flight reduced NiO sample shows a lower rate of reduction to metallic Ni and unreduced NiO. In-flight reduced NiO-Fe_3O_4 particle mixtures showed various peaks including unreduced

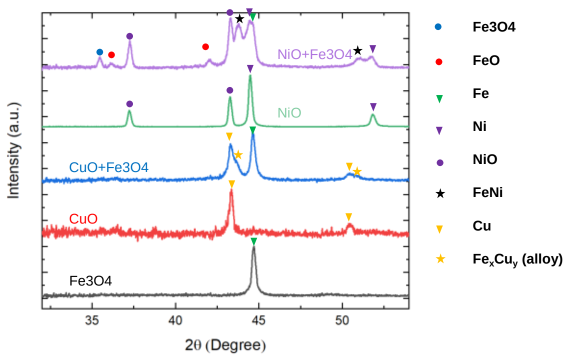

Fig. 1. X-ray diffraction patterns of in-flight reduced Fe_3O_4 particles, CuO particles, CuO-Fe_3O_4 mixture, NiO and NiO-Fe_3O_4 mixture.

Fe_3O_4, NiO, partially reduced FeO, metallic Fe and Ni, and FeNi. This indicates that the in-flight reduction technique not only shows a potential for carbon-free reduction of metal oxides besides iron oxides, but also exhibits the ability to synthesize nanometer-size metal alloys or compounds for a wide range of applications.

4. Conclusion

A novel method was introduced to reduce metal oxides using an atmospheric pressure hydrogen plasma. Magnetite particles could be reduced in-flight, with the filter collecting metallic iron. The reduction process achieves 100 times faster than the previously reported flash in-flight iron ore reduction by thermal hydrogen. This technique shows the potential for the reduction of various metal oxides and the ability to synthesize nanometer-size metal alloys or compounds.

Acknowledgment

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