Abstract

Prof. Dr. habil. Dr. h.c. Dierk RAABE

Managing Director, Max Planck Institute for Sustainable Materials, 40237 Duesseldorf, Germany

Transport and phase transformations phenomena in sustainable hydrogen-based steel production

Iron- and steelmaking stand for about 8% of all global greenhouse gas emissions, which qualifies this sector as the biggest single cause of global warming [1,2]. This originates from the use of fossil carbon carriers as precursors for the reduction of iron oxides. Carbon is turned in blast furnaces into CO and – through the redox processes reducing iron oxide – into CO2, producing about 2 tons CO2 for each ton of steel produced.

Mitigation strategies pursue the replacement of fossil carbon carriers by sustainably produced hydrogen and / or electrons as alternative reductants, to massively cut these CO2 emissions, thereby lying the foundations for transforming a 3000 years old industry within a few years [1,2].

As the sustainable production of hydrogen using renewable energy is a severe bottleneck in green steel making, at least during the next decade (transforming this industry would need about 300 Million tons of green hydrogen each year, i.e. about 5 orders of magnitude more than produced around the globe today), the gigantic annual steel production of 1.85 billion tons requires strategies to use hydrogen and / or electrons very efficiently and to yield high metallization at fast reduction kinetic.

This presentation presents progress in understanding the governing mechanisms of hydrogen-based direct reduction and plasma reduction of iron oxides [2-5]. The metallization degree, reduction kinetics and their dependence on the underlying redox reactions in hydrogen-containing direct and plasma reduction strongly depend on mass transport kinetics, Kirkendall effects, nucleation phenomena during the multiple phase transformations, chemical and stress partitioning, the oxide's chemistry and microstructure, the acquired (from sintering) and evolving (from oxygen loss) porosity, crystal plasticity, damage and fracture effects associated with the phase transformation phenomena occurring during reduction [5-8]. Understanding these effects, together with external boundary conditions such as other reductant gas mixtures (including also ammonia [8]), oxide feedstock composition [9], pressure and temperature, is key to produce hydrogen-based green steel and design corresponding direct reduction shaft or fluidized bed reactors (with and without plasma support), enabling the required massive C02 reductions at affordable costs. Possible simulation approaches that are capable of capturing some of these phenomena and their interplay are also discussed [3-8].

1. Raabe, D., Tasan, C. C. & Olivetti, E. A. Strategies for improving the sustainability of structural metals. Nature 575, 64–74 (2019).

2. Raabe, D. The Materials Science behind Sustainable Metals and Alloys. Chem. Rev. 123, 2436–2608 (2023).

3. Kim, S. H. et al. Influence of microstructure and atomic-scale chemistry on the direct reduction of iron ore with hydrogen at 700°C. Acta Mater. 212, 116933 (2021).

4. Souza Filho, I. R. et al. Green steel at its crossroads: Hybrid hydrogen-based reduction of iron ores. J. Clean. Prod. 340, 130805 (2022).

5. Ma, Y. et al. Hierarchical nature of hydrogen-based direct reduction of iron oxides. Scr. Mater. 114571 (2022).

6. Ma, Y. et al. Hydrogen-based direct reduction of iron oxide at 700°C: Heterogeneity at pellet and microstructure scales. Int. J. Miner. Metall. Mater. 29, 1901–1907 (2022).

7. Bai, Y. et al. Chemo-Mechanical Phase-Field Modeling of Iron Oxide Reduction with Hydrogen. Acta Mater. 231, 117899 (2021).

8. Ma, Y. et al. Reducing Iron Oxide with Ammonia: A Sustainable Path to Green Steel. Adv. Sci. 2300111, 1–7 (2023).

9. Jovičević-Klug M, Souza Filho IR, Springer H, Adam C, Raabe D. 2024. Green steel from red mud through climate-neutral hydrogen plasma reduction. Nature. 625(7996):703–9