



Press Release

8 June 2026

Faster and more energy-efficient: Catalysts boost hydrogen-based steel production

Nickel oxides accelerate hydrogen-based steel production by a factor of two

At a glance:

Challenge: Conventional steel and metal production is responsible for 10% of global CO₂ emissions. Hydrogen-based production offers a sustainable alternative, but is relatively slow and energy-intensive.

Research question: How to accelerate hydrogen-based metal production, particularly for steels?

Results: Nickel oxides act as catalytic precursors for the iron oxide reduction, making it twice as fast.

Outlook: By enabling faster and more energy-efficient reduction, this approach brings hydrogen-based steel production closer to practical industrial deployment.

Steel and metal production are among the largest contributors to global greenhouse gas emissions, accounting for approximately 10% of global CO₂ emissions. At the same time, modern technology fully relies on having tailored steels and metals for applications in fields such as mobility, energy, infrastructure, safety and medicine. Hydrogen-based metal production offers a promising and CO₂-free alternative and goes even further by integrating reduction, alloying and microstructure design into a single production step. However, hydrogen-based metal production still faces a number of challenges on its path to widespread adoption, one of which is the relatively slow reduction kinetics of metal ores at temperatures below 800°C.

A researcher team of the Max Planck Institute for Sustainable Materials (MPI-SusMat) has now made a significant breakthrough. They discovered that adding specific metal oxides as catalytic precursors can double the reduction kinetics of hydrogen-based metal production compared to uncatalyzed processes and allow a reduced energy use. The researchers have published their findings in the scientific journal *Nature Synthesis*.

Nickel oxides: the most promising catalyst for stainless and maraging steels

Conventional alloy production is typically a three-step process: first, reducing ores to metals, then mixing liquified elements to create an alloy, and finally applying thermomechanical treatments to achieve the desired properties. Each of these steps is energy-intensive and relies on carbon as both an energy carrier and a reducing agent, resulting in significant CO₂ emissions and a high energy consumption. The MPI-SusMat team showed before, that a hydrogen-based reduction process allows to merge these three process steps into one single step.

Dr.-Ing. Xinren Chen, postdoctoral researcher at MPI-SusMat and first author of the latest publication and his colleagues now show that this approach not only reduces



carbon emissions by using hydrogen as the reducing agent, but can also fundamentally accelerate the reaction kinetics.

The team demonstrates how this one-step metallurgical process can be enhanced by adding nickel oxide during the hydrogen-based reduction of iron ores to iron-nickel alloys. The additional nickel oxides are co-reduced and form nanoporous nickel as a transient phase. This nanoporous nickel acts as a highly active catalyst precursor for the reduction of iron oxides and enhances their reduction rate.

“Adding nickel oxides to an ongoing reduction process of iron oxides, makes the overall reduction twice as fast. Atom probe tomography combined with transmission electron microscopy revealed that as the nickel oxides are rapidly reduced to porous metallic nickel, they bind with neighbouring iron oxides and create an interface. When hydrogen as the reducing agent hits this interface, the nickel helps split the hydrogen molecules into highly reactive hydrogen atoms. These atoms then move across neighbouring iron oxide surfaces, a process known as hydrogen spillover, enabling accelerated reduction reactions. Notably, the reduction can initiate at temperatures as low as 300°C, well below the ignition point of hydrogen”, explains Chen.

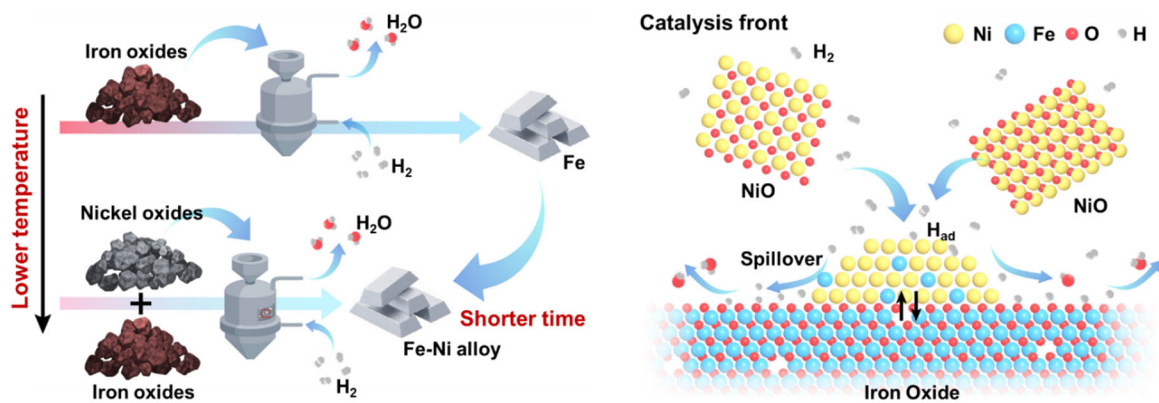
The resulting nickel-containing alloy is an important master alloy widely used in industrial steels, including stainless steels grades 304 and 316, as well as high-strength and cryogenic steels used for automotive, energy and medical applications.

Do other metal oxides have the same catalytic effect?

Using nickel oxides, the researchers successfully accelerated hydrogen-based iron ore reduction. Nickel is both thermodynamically and metallurgically compatible with iron, making it particularly effective in this process. “While other transition metal oxides have not yet been systematically evaluated, elements with similar properties, such as cobalt, are expected to exhibit comparable catalytic behaviour, offering promising directions for future investigation. In addition, oxides such as TiO₂, although not readily reducible under these conditions, may also facilitate hydrogen spillover by providing active surface pathways for atomic hydrogen migration”, says Professor Dierk Raabe, managing director of MPI-SusMat and corresponding author of the publication.

Taken together, these results demonstrate that alloy formation and reduction can proceed simultaneously, rather than through the conventional sequence of post-reduction interdiffusion. This coupling of processes enhanced by metal oxide catalysts enables lower reduction temperatures, shorter processing times, and reduced energy consumption, opening up a more sustainable one-step route for producing iron-nickel master alloys. Beyond this specific system, the findings offer new mechanistic insights that could help drive a significant advance towards more energy-efficient and accelerated metallurgical extraction processes.

At MPI-SusMat, sustainable metal and alloy production is being explored from multiple perspectives, combining experimental and theoretical approaches. In solid-state direct reduction, the kinetics are governed by a complex interplay of factors including temperature, the choice of reductant and metal system, and catalytic effects. A deeper understanding of these coupled mechanisms is essential for guiding the development of next-generation, more sustainable and cost-efficient reduction technologies.



Nickel oxides serve as a catalyst precursor and accelerate the reduction kinetics by a factor of two, compared to an uncatalyzed hydrogen-based reduction. This is possible as nickel oxides bind with neighbouring iron oxides, creating an interface. Nickel breaks the incoming hydrogen molecules into highly reactive hydrogen atoms. These atoms then move across neighbouring iron oxide surfaces, a process known as hydrogen spillover, enabling accelerated reduction reactions. Image taken from Nature Synthesis. DOI: 10.1038/s44160-026-01086-5.

Original publication:

X. Chen, B. Bienvenu, T. Yang, B. Gault, S.L. Wei, X. Zhou, D. Raabe: Solid-solid catalysis for sustainable alloy synthesis. In: Nature Synthesis DOI: 10.1038/s44160-026-01086-5

Publication on single-step metallurgy:

S.L. Wei, Y. Ma, D. Raabe: One step from oxides to sustainable bulk alloys. In: Nature 2024, DOI: 10.1038/s41586-024-07932-w

At the Max Planck Institute for Sustainable Materials (MPI-SusMat), we develop new ways to design, produce, and recycle materials for a climate-neutral future. From green steel and circular aluminium to advanced batteries, our research tackles key challenges in energy, mobility, and resource efficiency. By combining cutting-edge materials science with artificial intelligence, we drive sustainable innovation. Until 2024, the institute was known as the Max-Planck-Institut für Eisenforschung GmbH.

Stay up to date and follow us on [LinkedIn](#), and [YouTube](#).

Contact:

Yasmin Ahmed Salem, M.A.
Press and Public Relations Officer
E-Mail: y.ahmedsalem@mpi-susmat.de
Tel.: +49 (0) 211 6792 722
<https://www.mpi-susmat.de>

