



Press Release

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Turning scrap impurities into enhanced alloys

New machine learning framework makes metal recycling more sustainable without compromising on mechanical properties. Results now published in journal *Science Advances*.

At a glance:

- **Challenge:** Metal production consumes vast amounts of energy and generates significant CO₂ emissions. Recycling could reduce this environmental impact, but variations in scrap composition and unwanted impurities can reduce the mechanical properties of recycled alloys, limiting their industrial use.
- **New approach:** Machine-learning strategy to design high-performance alloys entirely using metal scrap.
- **Result:** 14 new iron-based alloys with increased tensile strength, elongation at fracture and decreased production costs, while avoiding the environmental impact of primary synthesis.

Around two billion tonnes of metal are produced worldwide every year to meet the demands of industry, infrastructure and the energy sector. Much of this production still relies on primary raw materials, contributing to an estimated 40% of industrial greenhouse gas emissions and 10% of global energy consumption. Increasing the use of recycled metals could significantly reduce the environmental impact of metal production while also lowering dependence on imports of scarce and strategically critical raw materials.

However, recycling metals comes with considerable challenges. Unlike primary raw materials, metal scrap often varies widely in its chemical composition and may contain unwanted elements. These variations can compromise the mechanical properties of recycled alloys, making it difficult to produce high-performance materials that meet demanding industrial requirements.

An international team of scientists has now developed a new machine-learning strategy that turns this challenge into an opportunity. Rather than treating impurities in metal scrap as unwanted contaminants, the researchers actively use them as alloying elements. The resulting so-called 'dirty alloys' are not only more tolerant of variations in scrap composition, but also come with enhanced mechanical properties and reduced production costs. The scientists published their findings in the journal *Science Advances*.

Artificial intelligence relates composition directly to alloy properties

"The conventional approach to dealing with impurities in metal scrap is to dilute them by adding virgin material. However, this undermines the environmental benefits of recycling, as producing virgin metals requires large amounts of energy and generates significant CO₂ emissions. We therefore developed a new machine-learning strategy that turns these impurities from a problem into an advantage, enabling us to design alloys that not only tolerate contaminants but can even benefit from them", explains Dr



Liuliu Han, partner group leader of the Max Planck Institute for Sustainable Materials and one of the corresponding authors of the recent publication.

The highlight of the new machine learning framework is that it links alloy composition and processing conditions to the desired performance without relying heavily on microstructural features. Starting from existing alloy designs, a tree-search algorithm generates new candidates by varying composition and processing parameters like temperature and time within predefined ranges. Neural-network models predict each candidate's tensile strength and elongation, guiding the search towards combinations that could improve on the best existing strength-ductility trade-offs. The algorithm balances refining promising designs with exploring less-tested regions of the design space. A second model, trained on a larger composition-property dataset, further screens the shortlisted candidates before selected designs are manufactured and tested. The experimental results are then added to the database to update the predictive model and guide the next optimization round, progressively improving the recommendations through a cycle of optimization and experimental feedback. This makes the approach faster and more feasible.

Dirty alloys with enhanced mechanical properties

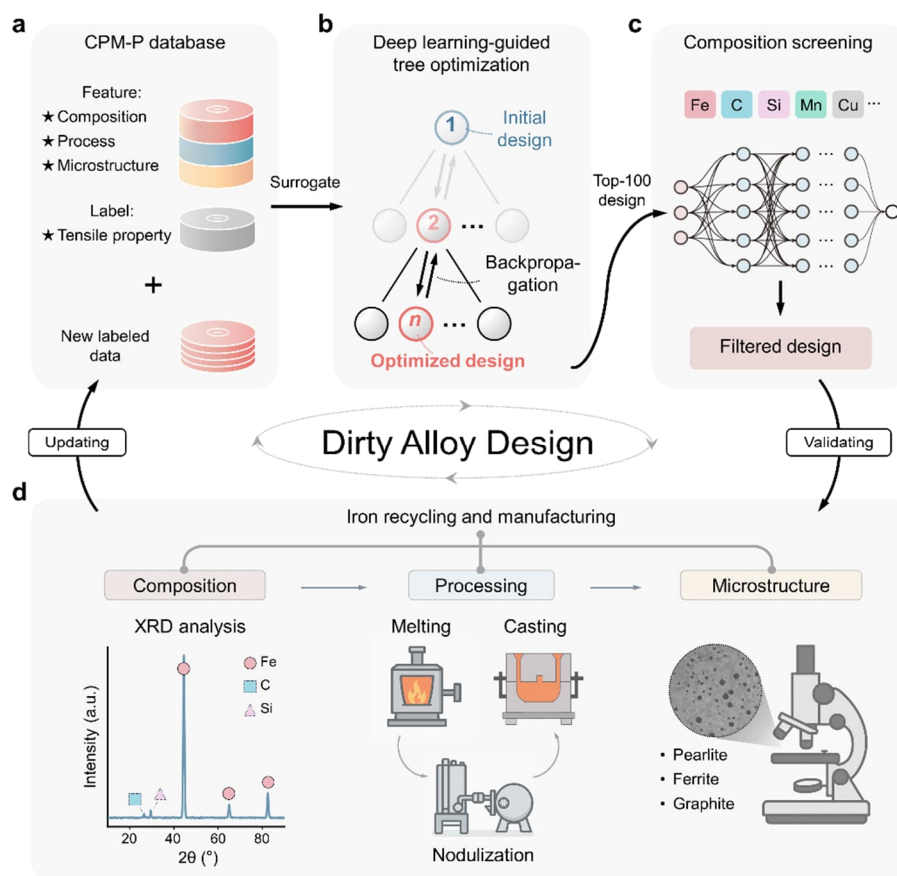
The scientists used ductile iron as their model material as it is known for its high impurity tolerance and industrial relevance, with 120 million tons produced annually worldwide. They tested 17 ductile-iron designs suggested by the framework; 14 proved to have the best combinations of strength and ductility in the existing recycled-iron dataset. Relative to that reference, tensile strength increased by up to 15.2% at comparable elongation, or elongation at fracture increased by up to 73.2% at comparable tensile strength. Also manufacturing costs were 8.1% lower than for the conventional route, which blends scrap with virgin iron.

The team showed how the properties of alloys made entirely from scrap can exceed materials made by primary synthesis and decrease their environmental impact. Looking ahead, the framework could be extended beyond ductile iron to recycled steels, aluminium and copper alloys, broadening its potential applications in transport, energy and industrial manufacturing. A promising next step would be to integrate multi-agent AI systems with automated experimental platforms, allowing specialized agents to coordinate alloy design, experimental planning, process control and interpretation of results. This could enable a more autonomous cycle in which experimental findings guide subsequent design and manufacturing decisions, accelerating alloy development while adapting to variations in scrap composition. Such advances could also help uncover new ways to use impurities as beneficial alloying elements.

The research was conducted by researchers from the Chinese Shanghai Jiao Tong University, the City University of Hong Kong, the East China University of Science and Technology, the Central South University and the German Max Planck Institute for Sustainable Materials.



Recycling metals comes with considerable challenges. Unlike primary raw materials, metal scrap often varies widely in its chemical composition and may contain unwanted elements. These variations can compromise the mechanical properties of recycled alloys, making it difficult to produce high-performance materials that meet demanding industrial requirements. Copyright: Adobe Stock 102472568



Dirty alloy design workflow: **(a)** Dataset that consists of composition, processing, and microstructure-related parameters (CPM-P). **(b)** Tree optimization guided by the convolutional



neural network surrogate model trained on the CPM-P dataset. (c) Composition-based filtering. (d) Ductile iron recycling and manufacturing pipeline, from which we extract comprehensive information about composition, process, and microstructure. From: Science Advances (2026). DOI: [10.1126/sciadv.aeg9183](https://doi.org/10.1126/sciadv.aeg9183)

Original publication

C. Yang, B. Peng, B. Sun, Q. Tao, Y. Zeng, L. Zhang, D. Shu, J. Lu, D. Raabe, L. Han, Y. Wei: From scrap to prime: designing high-performance alloys from dirty feedstock with machine learning. In: Science Advances 12 (2026). DOI: [10.1126/sciadv.aeg9183](https://doi.org/10.1126/sciadv.aeg9183)

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