A NOVEL TECHNIQUE FOR SCRAP STEEL CONSOLIDATION

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STEEL & SUSTAINABILITY

Protocols like the Paris Agreement stress the need for reducing greenhouse gas emissions in order to combat rising global temperatures. The steel industry, though having made marginal improvements in the sustainability space, is still largely not on track to meeting these sustainable development goals. Steel production has contributed to approximately 9% of global emissions over the past century, and as demand for steel products continues to increase, novel techniques alongside adequate buy-in will be necessary to cut the energy and byproducts associated with steelmaking.[1]

Electric Arc Furnaces

In the United States, over 70% of steel is manufactured using electric arc furnaces (EAFs).[2] EAFs send electricity between graphite electrodes with large voltage differences, which heats scrap iron and steel to their melting temperatures. The metal can then be shaped and fabricated in this molten state. Electric arc furnaces' use of recycled material and reliance upon electricity make them a large improvement over producing virgin steel from a blast furnace, as is typically done globally. However, they consume substantial amounts of power, to the extent that they often must be operated when electricity demand is low to avoid blackout scenarios.[3]

A Novel Technique Emerges

A new technique could prove to be instrumental in reducing the energy input in steel production. The approach, developed by researchers at MIT, revolves around recycling scrap steel using a much lower energy input than the electric arc furnace. The key is hot rolling the steel rather than melting it: the scrap is heated to high temperatures, packaged, and rolled together, resulting in a homogeneous steel product.

Hot Rolled Steel

Hot rolling steel is already common practice in metal forming. The metal is heated past its recrystallization temperature, which means that the grains of the metal are able to break down and reform in a stronger and more uniform manner. Adjacent rollers help compress the hot metal into uniform sheets and allow the slabs to be constructed into the desired shapes, as the reformed metal is tougher, more ductile, and easier to weld. Many steel structural components, pieces of agricultural and automotive equipment, and railroads are already constructed using hot rolled steel.[4] The novel approach is simply another application of this technique, leveraging existing infrastructure to provide a less energy-intensive alternative to EAFs.

Lower Energy Requirements

From a simplified estimation, the minimum energy required to melt steel in an electric arc furnace (without taking into account any losses of the system) would be the sum of the energy required to heat the steel to its melting temperature (about 1370°C) and the

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[1] Wang, "Efficiency Stagnation … "

[2] AISI, "Steel Production"

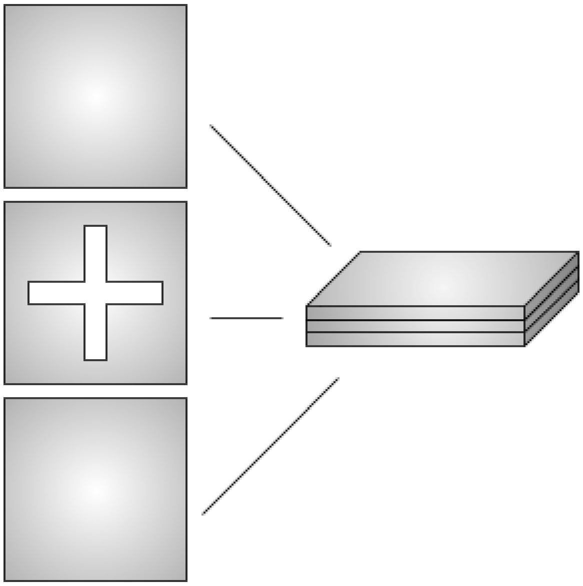
[3] Flournoy, "How Does an Electric Arc Furnace Work?"

[4] Corrosionpedia, "Hot Rolling"

energy required to change the phase from solid to liquid. For a kilogram of steel, this would be 817 kJ – approximately the same amount of energy as it would take to lift a sedan from sea level to a half mile in elevation. Meanwhile, heating the kilogram of steel to 1075°C, as in the hot rolling approach, only requires about half of that energy. The large energy savings, combined with the ease of utilizing existing hot rolling infrastructure, makes this a very attractive alternative.

THE PROCESS

Piecing It Together



The hot-rolled steel consolidation approach was tested in a laboratory setting in a manner that simulated the stochastic nature of a factory, in which irregular sheets of scrap metal may end up on top of one another, coplanar, or with gaps in between them at the commencement of the rolling process. The researchers modeled this by stacking three 30mm x 30mm sheets of 1010 mild steel on top of each other, with the middle layer containing a plus-shaped hole. The plus shape gave insight into how pieces that bordered each other laterally in the two extreme cases – parallel and perpendicular to the direction of rolling – would bond. The pre-measured gaps gave finer precision in controlling how far apart the pieces would be in order to test the extent to which the separation between the pieces mattered. Each piece was roughed with a wire brush to disturb any oxide layers that had built up on the surface and the three-piece units were enveloped in a stiff foil to constrain the layers together.

Rolling

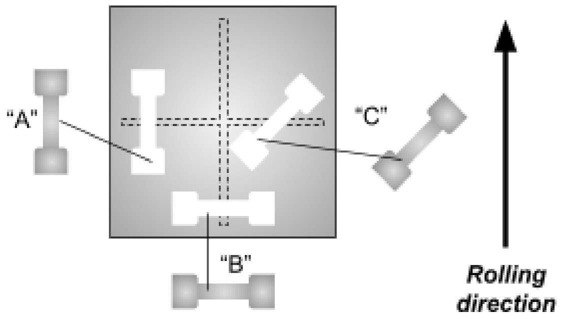
Each packet of steel was heated to 1075°C in a wall-powered furnace, which is between the recrystallization temperature and melting temperature of the steel and within the standard temperature range for hot rolling steel. Once the samples had reached this temperature, they were taken out and placed through the roller. They were then left to cool, and the researchers removed the foil. At this point, the steel was in its final state and could be post-processed as desired. The researchers performed tests to determine the efficacy of the process in bonding the pieces together.

QUALITY ASSURANCE

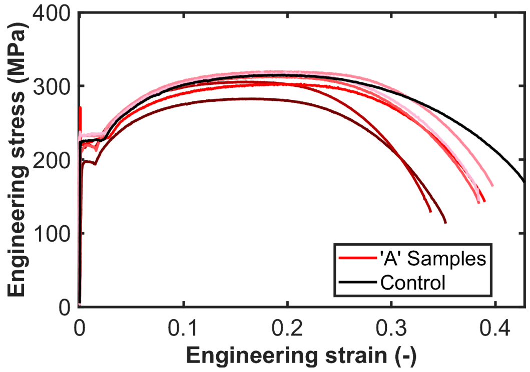
The researchers performed tensile tests of the hot rolled steel units to determine if the steel produced in this manner had desirable material properties. They ran tests with 1010 mild steel with widths of the plus-shaped gaps ranging from under 1mm to 2mm.

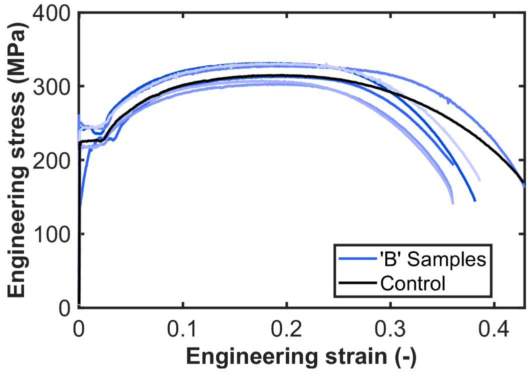
Tensile Testing

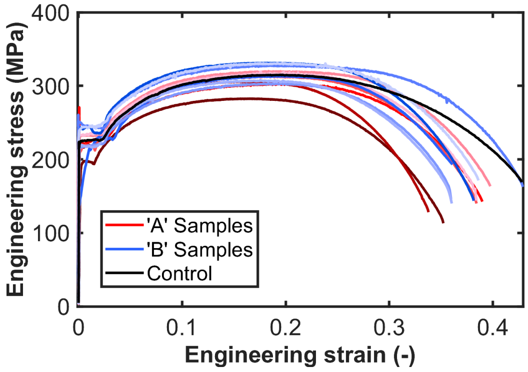
Each of the mild steel samples visibly bonded together and were consistently strong and tough upon testing. The researchers compared the stress, strain, and yield strengths of each sample with a control sample that consisted of three layers with no gaps. The “A” samples were cut across the horizontal branch of the plus, which was perpendicular to the rolling direction, while the “B” samples were cut across the vertical branch of the plus, which was parallel to the rolling direction. A “C” sample was also cut 45° offset from the rolling direction to analyze the strength of the bonding under shear forces.



The following images compare engineering stress and strain responses in samples cut normal to the gap, with the darker shades corresponding to greater plus-shaped gap thicknesses.

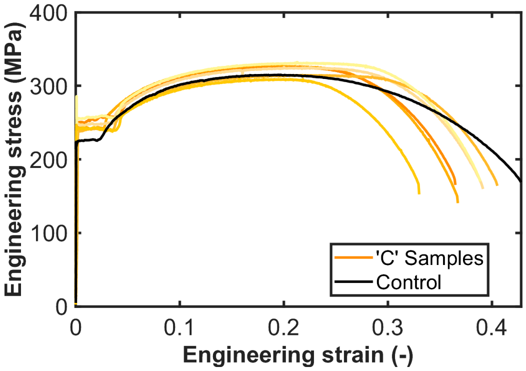




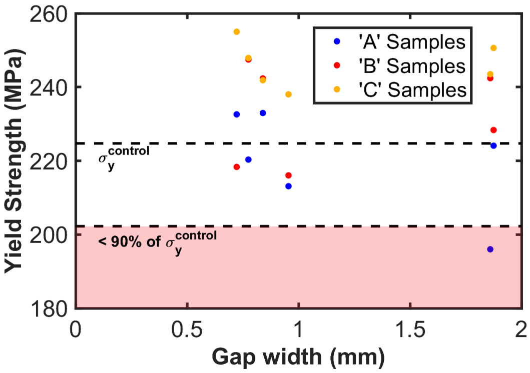


These graphs give insight into how the arrangement of scrap steel pieces would affect the response of the bulk steel product under loading. As a whole, there seemed to show a slight preference in the system for the “B” samples, which tended to be tougher and stronger, as well as samples that had lower gap thicknesses. However, even in the “worst case” scenarios with larger gaps perpendicular to the rolling direction, the material seemed to behave similarly to other samples before plastic deformation, and failure did not drastically precede that of the control. This is encouraging for use in the factory, as employers of this technique would not need to pay delicate attention to the orientation of chips or shards of steel when rolling, ensuring a less labor-intensive process.

While the “A” and “B” samples showcase how initial steel geometry affects the stiffness and toughness of the hot-rolled steel in different directions, the “C” samples serve as a comparison for how different load states could affect the output steel. The “A” and “B” samples were loaded such that they were pulling against the original site of the gap, so if the metal had not uniformly bonded and there were a seam in the final product, the axial tension would create large stress concentrations at the seam and pull it apart. The “C” samples, on the other hand, was pulled at a 45° angle with respect to the gap, illuminating how the steel would behave under shear loads.These samples exhibited similar behavior to the axially loaded samples, confirming that orientation does not need to be duly noted in either forming or employing the hot-rolled steel. This robustness drastically eases the implementation of this technology.



When the strengths of the material were taken into consideration, as seen below, all samples but one exceeded 90% of the yield strength of the control, a metric defined by the researchers as hallmarking a "successful" bond, with two thirds of these strengths even exceeding that of the control. Especially given that steel produced domestically via recycling is not typically implemented in high-performance applications, this approach could be sufficient and competitive with electric arc furnaces in the United States, even in less controlled settings than the laboratory.



IMPLEMENTATION

The success of this approach in the laboratory invokes the potential of being used in industry. The idealized implementation would involve collecting shards of scrap steel – including chips cast as byproducts from machining operations or waste steel at the mill – and packaging them in house. This would close material loops and thus increase efficiencies in production. Steel could also be sourced from metal recycling plants to increase yields. All of the scrap would be heated to the requisite temperature with electric power and fed en masse through the existing rolling machinery into a usable product.

Challenges

Numerous challenges would have to be overcome to employ this technology on a large scale. The first depends on recycling infrastructure – oftentimes the chemistry of scrap metal is not precisely known, and if the process works for some alloys of steel but not others, it may be difficult to know whether inputs are compatible. This could be partially mitigated by only using known stock or reusing steel that comes directly from the mill, but that would reduce its margin of impact.

Another challenge relates to the throughput and adoption of the process. Implementing a novel method takes buy-in and procedural changes, which can be difficult to supersede given the bureaucracy of large systems. Moreover, the technique would have the greatest impact if it were replacing a blast furnace primary steel production line rather than an electric arc furnace, but convincing these heaviest polluting producers to change their methods can be even more challenging. Beyond this, scaling up production from very small and controlled scales in the laboratory to large-scale packaging and heating will require logistical deliberation.

Future Work

This technique is still under refinement to prepare for real-world implementation. Currently, the effects of alternative process parameters, geometries, and materials are undergoing study, and future developments may include the further study of material toughness, increases to chip bonding efficacy, flux use cases, and improvements to stainless steel bonding conditions.

CONCLUSIONS

Hot rolling scrap steel provides an accessible, sustainable alternative to manufacturing recycled steel at scale. The energy savings, implementation of existing infrastructure, and simplicity of the technique demonstrate compelling advantages to its use over conventional steel manufacturing methods. The resulting product is strong, tough, and suitable for a wide array of structural applications.

SOURCES

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3. Flournoy, B., 2022. “How Does an Electric Arc Furnace Work?” [Online]. Available: https://www.hunker.com/12608288/how-does-an-electric-arc-furnace-work

4. Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., and Chen, W.-Q., 2021, “Efficiency Stagnation in Global Steel Production Urges Joint Supply- and Demand-Side Mitigation Efforts,” Nat Commun, 12, p. 2066.