Steelmaking on Mars

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Steel is Good

Arguably the most useful material on Earth:
- Cheap
- Strong
- Lightweight
- Recyclable
- Versatile

The basic material for sustained development in modern industrial society.

Used for everything from pins to bridges. Cars, ships, planes, cutlery, pots & pans, tools, fasteners, beams, pipe, wire, reinforcement bars, machinery, fences, buildings, appliances, furniture, etc., etc.

ISRU: Locally-produced steel on Mars a key component of self-sufficient colony. Enables maintenance and expansion.
What is Steel, Anyway?

- Modern definition is “any iron alloy that can be plastically formed”, e.g. rolled, pounded.
- Except for a few new alloys, steel contains 0.05 - 2.1% carbon.
- Small amounts of impurities such as sulphur, phosphorous, nitrogen, etc.
- Some silicon.
- Alloying elements are often added to enhance properties, e.g. chromium and nickel in stainless steel. Others: vanadium, magnesium, tungsten, etc.
- Most common is **mild carbon steel**, i.e. Fe with 0.05 - 0.26% C.
Quick Review: Steelmaking on Earth

- Modern steelmaking plants fully integrated, basic materials input, finished product output.
- Two main streams:
  - **Ore-to-steel**: blast furnace & basic oxygen furnace (BOF)
  - **Scrap-to-steel**: electric arc furnace (EAF)
- An iron ore process will be needed on Mars first. (Scrap stream comes later.)
Iron Ore → Steel
The Blast Furnace

• Ore refined in a blast furnace. Vertical chamber made from refractory bricks, designed for temperatures up to 2200°C.

• 4 ingredients:
  1. Iron ore, in the form of lump ore, pellets and/or sinter. Ore is received as lump ore or fine ore. Fines must first be agglomerated into larger particles, either pellets or sinter.
  2. Coke: mostly solid carbon, formed from coal that has been treated to remove impurities.
  3. Flux: usually limestone (CaCO\(_3\)), magnesite (MgCO\(_3\)), dolomite (CaMg(CO\(_3\))\(_2\)) or some combination of these.
  4. Oxygen.

• Ore, coke and flux are “charged” (added) into the top of the furnace. Oxygen blasted into the bottom.
**Iron Ore → Steel**

**Reducing the Iron Oxide**

- Coke burns, maintaining high T:
  \[ 2C + O_2 = 2CO \]

- CO reduces about 75% of the iron ore (nominally hematite):
  \[ Fe_2O_3 + 3CO = 2Fe + 3CO_2 \]

- The rest is reduced by C:
  \[ Fe_2O_3 + 3C = 2Fe + 3CO \]

- Some C also dissolves in the Fe:
  \[ 3Fe + C = Fe_3C \]
Flux is used to dissolve impurities, mostly silica (SiO$_2$).

Limestone decomposes to quicklime in the heat of the furnace:

$$CaCO_3 = CaO + CO_2$$

Quicklime combines with silica to form calcium silicate slag:

$$CaO + SiO_2 = CaSiO_3$$

Slag is lighter than the molten metal, floats on the surface and can be poured off.

Different fluxes can be used to remove different impurities.
Iron Ore $\rightarrow$ Steel

The Basic Oxygen Furnace

- The resulting hot metal has too much carbon, up to 7%.
- C removed in a BOF. Oxygen blown into the molten metal, oxidising C to CO$_2$ gas.
- Will still have too much silicon, sulphur, and phosphorous.
- Flux again used to remove impurities, slag formed and removed.
- Process controlled by computers, and continued until carbon and other elements reduced to desired levels.
The Basic Oxygen Furnace
Alloying metals may then be added, and the steel is continuous cast into strands for cutting and rolling into product.
Steelmaking on Mars

Challenges:
- No coal or natural gas (we think).
- Concentrated deposits of carbonates?
- Very little gaseous O$_2$.

However, basic materials are available:
- Iron everywhere.
- Carbon in air (CO$_2$).

Hence, just need new techniques.

5 alternatives examined:
- Carbon Method
- Carbon Monoxide Method
- Methane Method
- Hydrogen Method
- Carbonyl Method
Carbon Method

- Simplistic approach: manufacture same ingredients, and use same equipment.
- Solid C can be manufactured from Martian air via the Bosch reaction:
  \[ \text{CO}_2 + 2\text{H}_2 = \text{C} + 2\text{H}_2\text{O} \]
- Not ideal. Requires an iron, cobalt or nickel catalyst, which would have to be mechanically cleaned to isolate solid carbon. (Inefficient, slow, problematic)
- \(\text{H}_2\) for above reaction, plus \(\text{O}_2\) for coke burning and BOF, can easily be produced by electrolysis of water:
  \[ 2\text{H}_2\text{O} = 2\text{H}_2 + \text{O}_2 \]
  Electrolysis a well-developed technology that will probably already be in industrial-scale use on Mars.
Obtaining Carbonate Flux

According to current research:

- Mars surface dust about 2-5% carbonates, uniformly spread across Mars, not in concentrated deposits as expected if Mars was once wet.
- However: carbonate dust could be erosion products, spread by wind. Carbonate rock layers may exist, hidden below the dust.
- Not yet known exactly what carbonates, but magnesite (MgCO$_3$) fits thermal emission data (from TES) best.

- There may be methods to concentrate flux from dust, or there may be cheaper alternatives.
Carbon Monoxide Method

- CO primary reducing agent in ore-to-steel process and easier to make than C.
- Bypass burning of coke.
- Make CO with Reverse Water Gas Shift (RWGS)
  \[ \text{CO}_2 + \text{H}_2 = \text{CO} + \text{H}_2\text{O} \]
  Endothermic, requires iron-chrome catalyst.
- Direct reduction of atmospheric \( \text{CO}_2 \) also an option, but harder to do industrially.
Carbon Monoxide Method: 

**Energy**

- Coke-burning reaction maintained high temperatures required (above Fe melting point).
  - Need to provide this energy some other way, e.g. use graphite electrodes as in an EAF.
- Resulting reduced iron will not contain dissolved carbon, which will still need to be added. May still require manufacture of solid carbon (although considerably less).
Fe might be Ok

- Iron will be suitable for many applications on Mars:
  - Reduced loads in 0.38g.
  - Much lower wind loads in 0.8kPa atmo.
  - Can always make thicker beams if required.

- Sometimes Fe might even be better.
  - Mars very cold. Fe remains ductile at lower temperatures than steel, which becomes brittle in extreme cold.
**Methane Method**

- **Direct Reduction**: On Earth, uses natural gas (methane) instead of coal.
- Iron produced called DRI (*Direct Reduced Iron*). Usually combined with scrap in electric arc furnaces.
- DR furnace operates at lower temperature – Fe not melted.
- Normally, high-grade ore is used because impurities are not removed.
- DRI contains 1% - 3.5% carbon.
Direct Reduction Chemistry

- Methane partially oxidised to form reducing gases:
  \[2\text{CH}_4 + \text{O}_2 = 2\text{CO} + 4\text{H}_2\]

- Reduction of iron oxide:
  \[\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2\]
  \[\text{Fe}_2\text{O}_3 + 3\text{H}_2 = 2\text{Fe} + 3\text{H}_2\text{O}\]

- Reactants reformed into more reducing gas:
  \[\text{CH}_4 + \text{CO}_2 = 2\text{CO} + 2\text{H}_2\]
  \[\text{CH}_4 + \text{H}_2\text{O} = \text{CO} + 3\text{H}_2\]

- Carburisation reactions:
  \[3\text{Fe} + \text{CO} + \text{H}_2 = \text{Fe}_3\text{C} + \text{H}_2\text{O}\]
  \[3\text{Fe} + \text{CH}_4 = \text{Fe}_3\text{C} + 2\text{H}_2\]

- Reactions occur at lower temperatures – less energy required.
Direct Reduction

Reduction:
\[ \text{Fe}_2\text{O}_3 + 3\text{H}_2 \rightarrow 2\text{Fe} + 3\text{H}_2\text{O} \]
\[ \text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2 \]

Carburization:
\[ 3\text{Fe} + \text{CO} + \text{H}_2 \rightarrow \text{Fe}_3\text{C} + \text{H}_2\text{O} \]
\[ 3\text{Fe} + \text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 2\text{H}_2 \]

Reforming:
\[ \text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \]
\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \]


Methane Manufacture

- Use well-described and experimentally verified processes (In-Situ Propellant Production).
- Sabatier reaction:
  \[ \text{CO}_2 + \text{H}_2 = \text{CH}_4 + \text{H}_2\text{O} \]
- Cheap & easy. Probably will already be in industrial-scale use on Mars for rover and rocket fuel, plastics and hydrocarbons, and maybe even as a greenhouse gas.
- \( \text{H}_2 \) & \( \text{O}_2 \) produced from electrolysis.
Methane Method: Advantages

- Does not require manufacture of solid C.
- Methane factory already part of base, may be available in abundance.
- Uses well-developed and understood technology & equipment.
- DR methods also exist that use fluidised beds to reduce fine ore. Eliminates the need for sintering or pelletising.
Materials Flow: the Basics

These elements already part of Mars base:
Methane Method:  
*Flow Diagram*

- Emphasis on recycling.  Reuse offgas.  Slag used as cement substitute, or to enrich soil, as on Earth.
Hydrogen Method

- All previous methods require hydrogen to produce the reducing agent.
- Cheaper/simpler to just use the hydrogen:
  \[ \text{Fe}_2\text{O}_3 + 3\text{H}_2 = 2\text{Fe} + 3\text{H}_2\text{O} \]
- Same problem as CO - resulting metal contains no dissolved carbon.
- Good method for making iron/DRI.
Hydrogen Method: 
*Add Carbon from CO\textsubscript{2}*

**Key concept:** Add carbon using the Bosch reaction inside the furnace:
\[
\text{CO}_2 + 2\text{H}_2 = \text{C} + 2\text{H}_2\text{O}
\]

- Reaction is accelerated by an iron catalyst – furnace is full of iron.
- On Mars, both \( \text{H}_2 \) and \( \text{CO}_2 \) very cheap (compared with previous alternatives \( \text{C}, \text{CO}, \text{CH}_4 \)).

**Other advantages:**
- Solid carbon does not need to be made separately.
- Bosch reaction exothermic, and can maintain furnace temperatures, i.e. lower energy costs.
- Computers can adjust \( \text{H}_2-\text{CO}_2 \) mixture to precisely control the amount of dissolved carbon.
Hydrogen Method: Implementation

- Reaction temperatures: Bosch reaction occurs at 450°C-600°C, whereas iron melts at 1538°C. Need to melt iron to remove impurities via flux slag technique.
- Hence, plant with two components:
  - Low-T furnace to reduce iron oxides and add carbon using H\textsubscript{2} and CO\textsubscript{2}. Produces DRI.
  - High-T furnace using oxygen and flux to remove impurities and control steel chemistry. Use an EAF.
- Overall process very similar to DR \(\rightarrow\) steel.
- Untested technology – would need to verify, build and fine-tune plant on Earth before sending to Mars.
Hydrogen Method: Flow Diagram

- All input gases cheap, on Mars.
- Recycle offgas, slag.
Carbonyl Method

- Usually used in nickel refining, or to produce high-purity iron.
- **Main benefit** – straight from ore to iron.
  - **DOES NOT REQUIRE FLUX**, i.e. very useful if concentrated carbonate deposits not found.
- 1. Iron oxides reduced (e.g. using \( \text{H}_2 \)).
- 2. Pressurize reduced iron with CO gas.
- 3. Fe combines with CO to form iron pentacarbonyl gas, \( \text{Fe(} \text{CO})_5 \). Piped to deposition chamber.
- 4. Exposing carbonyl gas to hot surface causes Fe to be deposited and CO gas released (can be used to directly produce iron beams, pipes, plate, sheet, vessels, etc.).
- 5. CO recycled back to first chamber.
Carbonyl Method: Adding Carbon from CO

Can add carbon via similar process as described in Hydrogen Method, but use CO instead of CO\(_2\):

\[
\text{CO} + \text{H}_2 = \text{C} + \text{H}_2\text{O}
\]

Sensors/computer adjust H\(_2\) input to control concentrations of dissolved C. May be more precise than using CO\(_2\) as in H method, because impurities removed first.

Deposit iron and carbon at the same time – straight from ore to steel without melting!
Carbonyl Method: Flow Diagram

Note absence of magnesite mine.
Conclusions

Steel can be made on Mars from local ingredients, various options.

Concentrated carbonate deposits will be valuable – must search for them beneath Martian dust.

Methane Method has merit.
- Uses well-understood and developed technology: Direct Reduction.
- Methane probably manufactured in large quantities anyway.

Hydrogen Method attractive due to low cost of ingredients. Method and equipment needs to be verified and tested.

Carbonyl Method could be best. Effective for pure Fe, does not require flux. Need to verify processes for adding carbon.