From mine to part: directed energy deposition of iron ore

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Abstract

Purpose – This paper aims to gain an understanding of the behaviour of iron ore when melted by a laser beam in a continuous manner. This fundamental knowledge is essential to further develop additive manufacturing routes such as production of low cost parts and *in-situ* reduction of the ore during processing.

Design/methodology/approach – Blown powder directed energy deposition was used as the processing method. The process was observed through high-speed imaging, and computed tomography was used to analyse the specimens.

Findings – The experimental trials give preliminary results showing potential for the processability of iron ore for additive manufacturing. A large and stable melt pool is formed in spite of the inhomogeneous material used. Single and multilayer tracks could be deposited. Although smooth and even on the surface, the single layer tracks displayed porosity. In case of multilayered tracks, delamination from the substrate material and deformation can be seen. High-speed videos of the process reveal various process phenomena such as melting of ore powder during feeding, cloud formation, melt pool size, melt flow and spatter formation.

Originality/value – Very little literature is available that studies the possible use of ore in additive manufacturing. Although the process studied here is not industrially useable as is, it is a step towards processing cheap unprocessed material with a laser beam.

Keywords Additive manufacturing, Additive manufacturing, Laser cladding, Crushed iron ore, High-speed imaging, Laser metal deposition

Paper type Research paper

Introduction

Laser additive manufacturing with a powder feedstock is a technique, which is growing in popularity in industry. One of its limitations is the high cost of high quality spherical powders generally used in processes such as directed energy deposition (DED or laser metal deposition [LMD]) or laser powder bed fusion (LPBF).

Several methods are used for producing powder, each resulting in specific characteristics. These methods are categorised into mechanical (such as atomisation processes and mechanical milling) and physical/chemical methods (such as electrolysis and chemical conversions). Gas atomisation is the most common process used to produce spherical powder with high purity, where molten metal is dispersed into small droplets by a high-pressure jet of inert gas (Antipas, 2013). Rotating electrode processes also exist and produce powder with larger diameters. Water atomisation uses high-pressure water as the atomising medium. It produces powders with irregular shapes because of the impact of the water. Plasma atomisation produces pure and high quality spherical powder and is often used for metals such as titanium. Mechanical milling uses a ball or rod mill to produce very fine powders, often from brittle materials, and can facilitate mechanical alloying. Plasma spherodisation is an additional treatment to change the shape of irregular powders to spheres and reduce porosity (Popovich and Sufiiarov, 2016).

The price of spherical powder available for laser additive manufacturing is strongly dependent on both the material composition and the production method. The price per kilogram of powder for an iron-based alloy ranges from 20 to 100 US$/kg, whereas the price of the raw materials, such as iron

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Rapid Prototyping Journal
27/11 (2021) 37–42
Emerald Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-10-2020-0243]

The work concerning this paper was funded by EU-ERDF Interreg Nord projects, C3TS No. 304-10694-2017 and CINEMA No. 304-7463-2018.

Received 12 October 2020
Revised 3 March 2021
23 April 2021
Accepted 25 May 2021

ore pellets ranged between 30 and 100 US$/tonne between the years 2015–20 (LKAB Sweden, 2020).

Several attempts have been made to use cheaper powders for the process. Water atomised powders and machining waste have been used to successfully produce tracks without significant defects (Pinkerton and Li, 2004a, 2004b; Mahmood *et al.*, 2011). Flowability of powders is a prerequisite for the DED process. Ball milled powders have been shown to have good flowability and can produce mechanically alloyed powders with homogenous composition, possibly for precision applications of DED (Khademzadeh *et al.*, 2015; *Additive Manufacturing of Metals*, 2020). The technique can also be used for producing composite powders for functionally graded laser clads (Pei *et al.*, 2011).

Very little literature is available regarding the use of near-unprocessed material such as iron ore in additive manufacturing. A study regarding the use of ore powder has been carried out for LPBF (Brandemyr, 2019). This present paper presents a study on the process observation and results concerning DED of iron ore.

The aim of this research is to gain improved understanding of the behaviour of iron ore when melted by a laser beam in a continuous manner, which has hardly been studied yet. This fundamental knowledge is essential to further develop two new additive manufacturing routes:

1 Manufacturing tailored low cost parts with relatively low mechanical demands. The material can achieve a rock-like mineral nature. Such parts might only be used once, for example support structures for sand in injection mould preparation, or spacer parts for packaging.
2 Instead of ore mining for steelmakers, ideally the reduction process of ore takes place during an additive manufacturing process by adding a suitable reducing agent. Another oxide can form that can be removed while iron remains, to be suitably alloyed, then solidifyed as a track, for steel part production. Corresponding research is in progress.

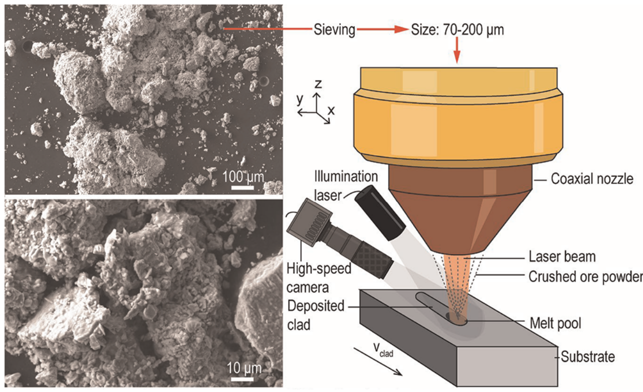
Today's steelmaking from iron ore is globally a main source for CO_2-emissions causing global warming. In Sweden more than 10% of all CO_2 emissions originate from the reduction process of iron ore to iron. When an environmentally friendly chemical reduction is found in an ore-based laser additive manufacturing process, CO_2 emissions will be avoided, to an extent proportional to its use. There are likely to be other advantages, which have huge potential. The basic knowledge studied in this paper about behaviour of iron ore melt when processed by a laser beam is an important first step towards such new additive manufacturing technique.

Materials and methods

After mining, iron ore undergoes crushing, magnetic separation of large impurities, concentration and pelletisation to increase its iron content. In this present work, waste collected during the pelletisation process starting with the magnetite ore at LKAB, Sweden (LKAB Sweden, 2019), was used as feedstock material in laser DED.

The ore powder received was dried for 24 h at 120°C and sieved to separate the size ranges 45–70 μm and 70–200 μm for the process. The powder particles were coarse and irregularly shaped, as can be seen in the SEM images in Figure 1(a). Stainless steel 316 L was used as the substrate material. The

Figure 1



(a) (b)

Notes: (a) SEM images (two magnifications) of the iron ore waste from the pelletizing process; (b) the experimental setup

chemical compositions of the substrate and powder materials are given in Table 1. Note that the composition of iron ore can vary from mine to mine.

Single and multilayered tracks were deposited by laser DED using a coaxial nozzle. The laser beam and shielding gas travel through a central hole in the nozzle, whereas the powder, along with the carrier gas, was fed through a ring-slit. Argon was used as both the shielding and carrier gas. Powder was fed through a commercial powder feeder. The processing laser was a diode laser with wavelength 980 nm and spot size 10 mm with a Gaussian distribution. The laser power ranged between 7 and 9.5 kW, the travel speed between 0.3–0.7m/min (5.00–11.67 mm/s) and the mass feed rate between 4.0 and 15.0 g/min (0.07–0.25g/s). The carrier gas flow was 15 L/min (0.25 L/s), and shielding gas flow was 30 L/min (0.50 L/s). The experimental parameters considered in this paper can be found in Table 2. The multilayer deposition was carried out with laser power 9 kW, travel speed 0.7 m/min (11.67 mm/s) and mass feed rate 15.0 g/min (0.25 g/s) with pauses for each layer to cool before deposition of the next layer. A schematic diagram of the experimental setup is presented in Figure 1(b).

High-speed imaging (HSI) was used for process observation. Videos were recorded from the side with the camera angled at 30° to the horizontal at frame rates of 5,000–10,000 frames per second. The videos were then played back at lower frame rates to observe the powder feeding and catchment behaviour, melt pool dynamics and solidification. After deposition, the specimens were inspected for porosity using computed tomography (CT).

Results and discussion

Tracks and walls could be deposited using iron ore onto a stainless steel substrate. Due to the characteristics of the ore powder, it was expected to form agglomerates and likely to have poor flowability. The flowability improved when the smaller size fraction (45–70 μm) was separated out of the powder. This outcome has also been reported regarding titanium sponge powders with irregular shapes (Amado *et al.*, 2019). After the

Table 1 Chemical composition of the powder and substrate material used in percentage

Material	Fe	O	Gd	Mg	Si	Ca	Mn	Ti	S	P	K	Cr	Ni	N	C
Ore	69.06	19.34	4.63	3.44	1.55	1.54	0.38	0.11	0.02	0.01	0.01	0	–	–	–
SS316L	Bal.	–	–	–	<0.75	–	<2	–	<0.03	<0.05	–	16– 18	10–14	<0.1	<0.03

Table 2 Experimental parameters

Parameter set no.	Laser power kW	Travel speed m/min (mm/s)	Mass feed rate g/min (g/s)
1	7	0.7 (11.67)	15.0 (0.25)
2	9	0.7 (11.67)	15.0 (0.25)
3	9.5	0.7 (11.67)	6.0 (0.10)
4	9.5	0.5 (8.33)	5.5 (0.09)
5	9.5	0.4 (6.67)	4.5 (0.08)
6	9.5	0.4 (6.67)	4.0 (0.07)
7	9.5	0.3 (5.00)	4.0 (0.07)

smaller particles had been removed, it was possible to feed the larger particles (70–200 μm) through a powder feeder.

While feeding the powder, a cloud of very fine ore particles is often formed between the nozzle and the melt pool/substrate. It is expected that this cloud attenuates the laser beam. The degree of attenuation is unknown but expected to vary depending on the characteristics of the cloud, leading to irregularities with the deposited clads. Attenuation of the laser beam is an established phenomenon in DED (Lia *et al.*, 2017) and is expected to be higher in case of powder particles with irregular shapes. Smaller powder particle sizes and high feeding rates increase the probability of forming the cloud, but its density varies randomly. It could also be seen from the high-speed videos that some powder particles arriving at the melt pool were spherical, implying that they had melted after absorbing enough laser radiation on their way to the melt pool. The cloud formed is marked in Figure 2(a), and the molten powder particles in Figure 2(b) deposited with parameter set number 1 from Table 2.

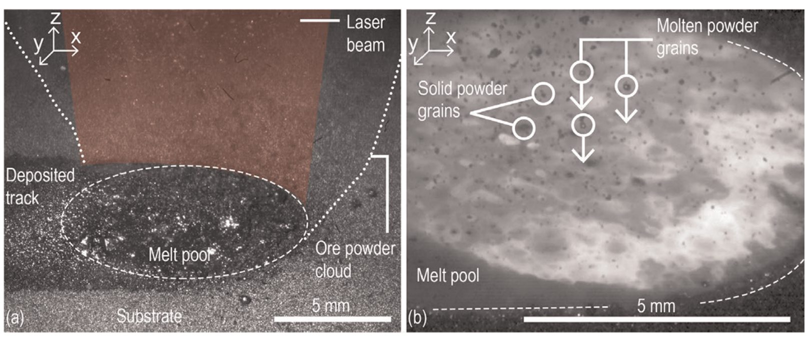
In spite of the ore being a geometrically and compositionally non-uniform, it was possible to form a stable melt pool and deposit tracks on the stainless steel substrate using laser DED. The size and characteristics of the melt pool depended on the laser energy density at the surface of the substrate. From Figure 3(a) (i–iii), it can be seen that a small melt pool with wetting around the edges or a large melt pool could form, with and without substrate melting (parameter set number 6, 2 and 7 from Table 2, respectively). Powder particles arriving at the melt pool float on the surface for a short time before incorporating. This phenomenon has been observed in other DED processes using gas atomised powders (Siva Prasad *et al.*, 2019; Siva Prasad *et al.*, 2020a, 2020b). During this time, they to travel (most often radially outwards) with the various melt pool flows, for example, Marangoni flow.

During the process, spattering was observed. A frame sequence from HSI showing spatter is presented in Figure 3(b)(i–iv). It is expected that spattering occurs due to the presence of low boiling elements in the ore powder such as phosphorous, sulphur, potassium, magnesium and calcium (Kaplan and Powell, 2011). In the high-speed videos, spattering was visible mainly from the front of the melt pool.

Figure 3(c) shows frames from HSI during multilayer deposition. The tracks become more uneven, and the length of the melt pool varies, depending on the geometry of the previous deposited layer. When several layers are deposited, delamination from the substrate can be seen, for example, in Figures 3(c)(iii) and 4(b). This occurs because of the presence of tensile stresses due to shrinkage during solidification. Delamination is expected to happen at the weakest area in the clad, in this case the transition between the substrate and the deposited tracks. Re-melting of a deposited track led to uneven results because of balling of the melt as a result of surface tension forces. Figure 3(b) and Figure 3(c) shows extracts from videos of experiments carried out using multilayer deposition parameters presented in the methods section of the paper.

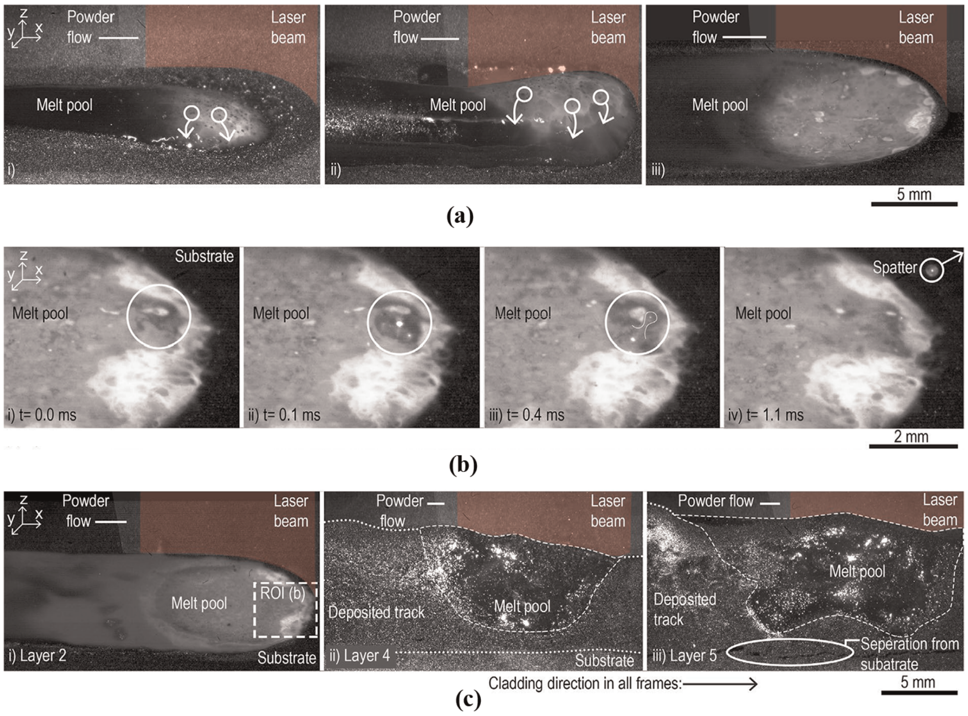
The deposited tracks and walls can be seen in Figure 4(a) and Figure 4(b), respectively. Some cracks were observed on

Figure 2 (a) Formation of a cloud and (b) melting of ore powder by the laser beam during feeding



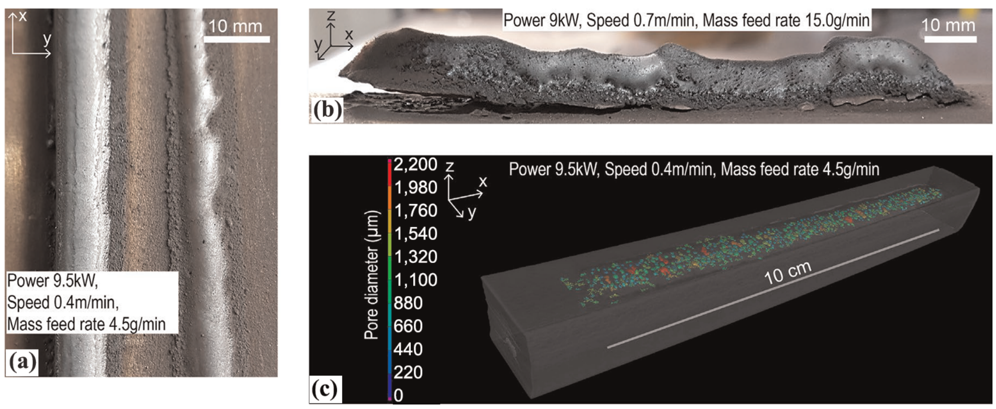
(a) (b)

Figure 3 Observations in the melt pool



Notes: (a) Single tracks deposited showing increasing amounts of substrate wetting and melting; (b) an image sequence showing generation of spatter from the melt pool; (c) the melt pool in multilayer deposition

Figure 4 (a) Deposited single tracks; (b) multilayered wall (6 layers); and (c) results from a CT scan of a deposited single track

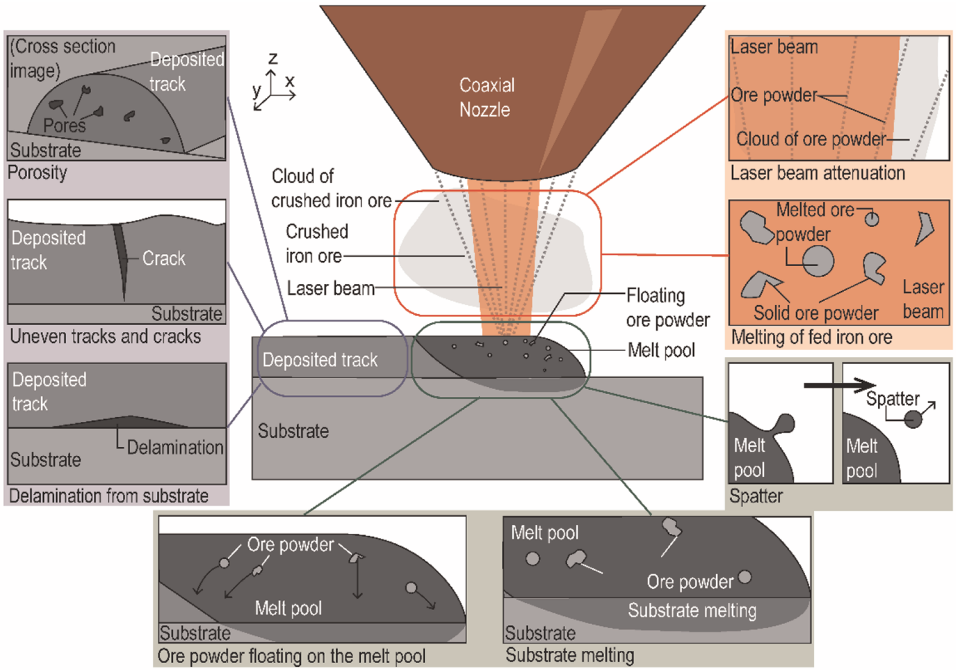


the walls and tracks. The CT results show a high degree of porosity in the tracks, an example of this is shown in Figure 4(c). Porosity may occur because of several reasons, such as:

- porous powder particles and entrainment of shielding gas trapped in the powder stream, worsened because of the non-optimal flow of irregularly shaped powder particles (Ng *et al.*, 2009);
- insufficient wetting and gas retention between powder particles (Siva Prasad *et al.*, 2020b);
- lack of fusion due to an insufficient capacity to melt the powder material (Ng *et al.*, 2009); and
- degassing of volatile constituents in the ore.

From EDX analysis of the ore melted using the laser beam, it could be seen that some areas have very high iron content (over 95%). Some elements such as calcium, phosphorous, potassium with low boiling points are lost during processing due to the high temperatures. However, extensive analysis needs to be done to make any conclusive statements.

Figure 5 Schematic illustration of the various phenomena observed during DED of iron ore



The various phenomena observed through visual inspection, HSI and the CT results can be categorised into three groups based on their location:

1 powder particle activity during feeding;
2 the melt pool dynamics; and
3 features of the solidified track.

These phenomena are presented schematically in Figure 5.

Conclusions

DED was carried out with waste from the iron ore pelletising process as the feedstock material:

- Irregularly shaped ore powder can be fed through commercial powder feeders and nozzle systems (but such powders might need to be filtered to reduce the range of particle sizes). A cloud of ore particles can form between the nozzle and the melt pool, leading to irregularities.
- Single tracks and multilayered walls can be deposited.
- A single, large and calm melt pool is formed in spite of the inhomogeneous feedstock material. Unmelted powder material can be seen floating on the surface of the melt pool. In addition, some powder particles melt on exposure to the laser beam during feeding to form spherical droplets before reaching the melt pool.
- The deposited single tracks were smooth and even on the surface. However, a high amount of porosity was present inside the tracks, likely due to entrapment of the feeding and shielding gases by the melt pool flows as well as degassing of volatile constituents in the ore.
- Deposition of several layers leads to a non-uniform wall build up. Compared to conventional materials, the deposited tracks are weak, leading to cracking and delamination.
- The process is not ready for application but describes the potential for use of cheap and near unprocessed powder in laser-based additive manufacturing processes. Further modifications of the powder or the process might yield direct use in industrial applications.

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