OVERVIEW OF DISPOSAL PROCEDURES FOR POWDER CONDENSATE WITHIN METAL POWDER BED FUSION

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Abstract

Powder condensate is the term used to describe solidified particles resulting from the evaporation of metal alloys during the powder bed fusion additive manufacturing (AM) process. This condensate, which is a waste stream unique to AM, is either deposited into a collection chamber within the AM printer (considered to be "dry" condensate) or wet-vacuumed out of the build chamber itself (considered, along with melt spatter contemporaneously removed, to be "wet" condensate). Both wet and dry condensate may be hazardous and must be disposed of pursuant to applicable environmental regulations. As metal AM is only now entering maturity with respect to production, powder condensate as a waste stream has previously neither been a major concern for operators nor studied widely. However, high volume manufacturers increasingly need to allocate proper resources for the safe disposal of this material. In order to do so, powder condensate should be classified as a separate waste stream and documented appropriately with cost-effective methods for its disposal. This paper discusses the procedures used in the United States for analyzing and disposing of condensate from the powder bed fusion process, and provides a real world example of how one high-volume manufacturer handles this disposal.

Introduction

Additive manufacturing, or 3D printing, is the process by which a raw material is transformed into a final finished or near finished part in a single step—with minimal waste—

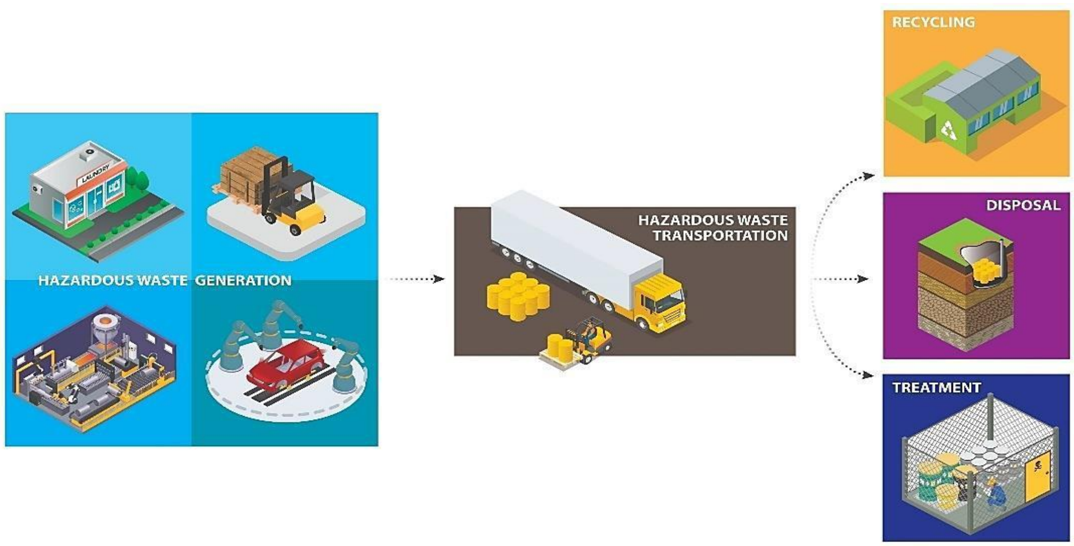
through the gradual addition of incremental layers of material. One of the most commercially successful methods of additive manufacturing is called metal powder bed fusion (PBF). PBF consists of a raw material, in this case virgin metal powder, which is loaded into a build chamber and melted by an energy source in consecutive layers. After a single layer is melted, the build plate descends by a designated height, followed by a re-coater arm programmed to sweep the next layer of powder over the prior layer. The process is then repeated until the part is completed and removed from the build chamber. Following its removal, the part undergoes additional steps including furnacing, machining, inspections, etc., until it is shipped to the customer.

The market size for additive manufacturing is growing rapidly and is expected to increase significantly in the coming years, with the PBF process projected to be a major driver of this growth. According to Grand View Research, "[the metal PBF] market size was valued at USD 772.1 million in 2019 and is expected to grow at a compound annual growth rate of 27.8% from 2020 to 2027." Major industries adopting PBF include automotive, aerospace, and healthcare industries, as PBF offers lower costs and weight reduction compared to traditional manufacturing, as well as allowing companies to produce more intricate and efficient designs.

As a new manufacturing technology, PBF unsurprisingly produces new waste streams, some of which may be hazardous. While AM waste streams typically represent a fraction of the waste produced in traditional manufacturing methods, they nonetheless represent a unique waste disposal challenge. As a result, diligent care must be taken by manufacturers to transport and dispose of these waste streams.

Background: United States EPA Regulations for the Generation, Transport, and Disposal of Hazardous Waste

Hazardous waste is defined as any solid or liquid waste that may exhibit certain characteristics as defined by the U.S. Environmental Protection Agency (EPA). The EPA regulates hazardous waste under the Resource Conservation and Recovery Act (RCRA) to ensure it is safely being managed to protect the environment and human health. The RCRA addresses the generation, transportation, treatment, storage, and disposal of all hazardous wastes under the method known as "cradle-to-grave," illustrated in Figure 1 below. Importantly, additive manufacturers, as with all manufacturers, are responsible for full life cycle disposal of their waste streams and must be fully aware of where (and by whom and treatment method) their hazardous waste is being permanently disposed.



<u>Figure 1: Cradle-to-Grave System</u>

Generally speaking, there are two main types of "industrial" waste: hazardous waste and regulated non-hazardous waste. Hazardous waste may be deemed as such due to ignitable, corrosive, reactive, radioactive, or toxic characteristics. Depending on the relevant classification, hazardous waste is assigned a "D" waste code (or F, K, P, and U in lesser cases) established by the EPA and shown in Figure 2 below. Once assigned a code, it must be controlled and transported in connection with U.S. Department of Transportation (USDOT) and RCRA guidelines. Regulated non-hazardous waste pertains to any substance that is concluded to be non-hazardous by certified lab technicians through testing and approved to be disposed of at a landfill.

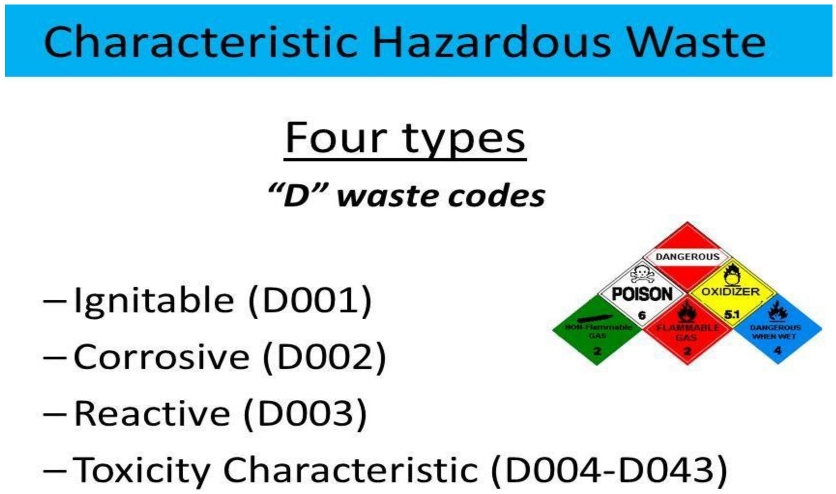


Figure 2: Hazardous Waste D Codes

For hazardous waste generators, EPA requirements include: (i) waste permits and an assigned EPA ID for the storage and handling of hazardous waste, (ii) written manifests for the hazardous material, (iii) quantity and proper record keeping of its generation, and (iv) an emergency action plan (EAP) for the company (including proper training).

For hazardous waste transportation (by ground, train, air, or water), it is critical that the hazardous waste is stabilized and contained for the entire length of transit. Also required is an EPA ID, to comply with the EPA's hazardous waste manifest system, and to obey all USDOT regulations. At the end location facilities, hazardous waste can be treated on site, stabilized and fully disposed of, or incinerated. A certificate of destruction can be made available and presented to the waste transporter as well as the hazardous waste generator.

For hazardous waste land disposal, according to the Hazardous and Solid Waste

Amendments to RCRA (HSWA), it is prohibited to dispose of untreated hazardous waste in a landfill. Certain concentration levels and methods of previous treatment is required by the EPA before land disposal to prevent health hazards. Alternatives to disposal are recycling solutions such as metal recovery or multipurpose energy sources. However, recyclability depends on the quality and ease of material recovery for reuse or resale and recycler certifications on what material properties and quantity are permitted.

PBF Raw Material: Powdered Metal Alloys

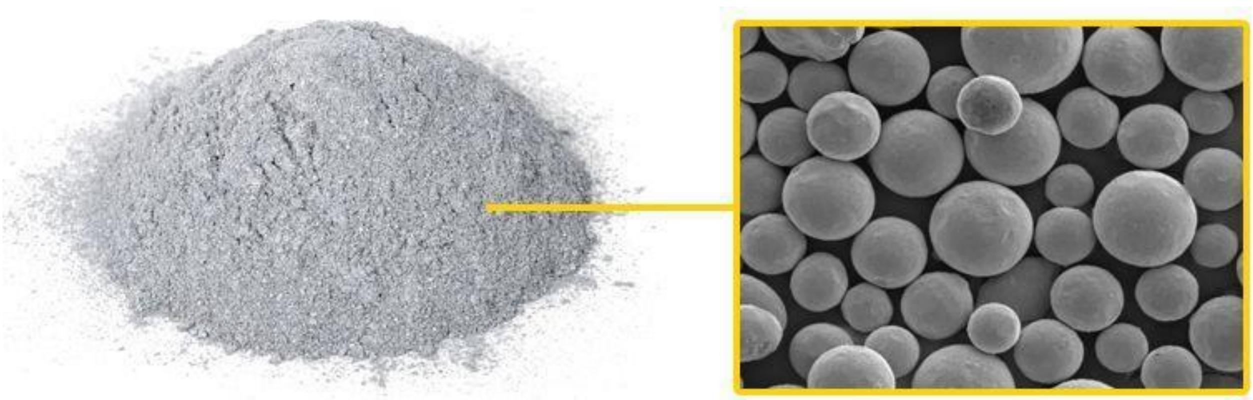


Figure 3: Powdered Metal at Microscopic Level

The raw material in the PBF process is processed metal powder. Common metal powders in production applications include nickel, steel, titanium, and aluminum alloys. Some of these alloys, such as nickel (Inconel 718 and Inconel 625) and steel (316L and 17-4PH), contain chromium, which is on the EPA's list of top 30 urban air toxic pollutants. Chromium content in condensate generated from these alloys often exceeds the EPA's allowance of 5 mg/L, and therefore must be treated as hazardous for toxicity. These alloys may also contain trace amounts of lead, although below the EPA's 5 mg/L limit.

While titanium and aluminum alloys do not have the same hazardous waste considerations specifically relating to chromium, both titanium and aluminum waste powder are considered reactive metals and may be ignitable (other metal condensate, including non-reactive metals, remain at risk for ignitability as well, due to particle size and morphology). It is of high importance that metal condensate from these alloys is kept inert per manufacturer and waste disposal company guidelines to avoid combustion in transport. The EPA utilizes three alternating test methods for ignitability. Wastes that are considered hazardous due to ignitability include "liquids with flash points below 60°C, non-liquids that cause fire through specific conditions, ignitable compressed gases and oxidizers." According to the ignitability of solids test method SW-846 Test Method 1030, "Wastes that have a rate of burning of more than 2.2 mm/sec (or burn time of less than 45 sec for 100 mm) are considered to have a positive result for ignitability according to USDOT regulations. For metals, this time is 10 minutes or less for 100 mm (or a burn rate of more than 0.17 mm/sec)."

Condensate Designation

Condensate is described as a vapor plume resulting from evaporation of a metal alloy during the AM PBF process[1]. The vapor is subjected to continuous gas flow within the build chamber which can rapidly solidify the condensate into particles. These condensate particles are made up of numerous metals, usually with hazardous and combustible elements. Dry condensate is carried away using the machine's inert gas flow, through a filter system, then deposited into a bin for removal. Wet condensate, which includes spatter, is suctioned out of the build chamber itself using a water based wet separator vacuum.

[1] Most PBF machines use lasers as energy sources, which operate in an inert build environment, as opposed to electron beam printers, which operate in a vacuum. In spite of this, electron beam printers have their own version of what could be considered dry condensate in the form of metallization sheaves that attach to the electron beam machine's heat shield, as well as wet condensate in the form of spatter that must be wet-vacuumed out (similar to laser machines).

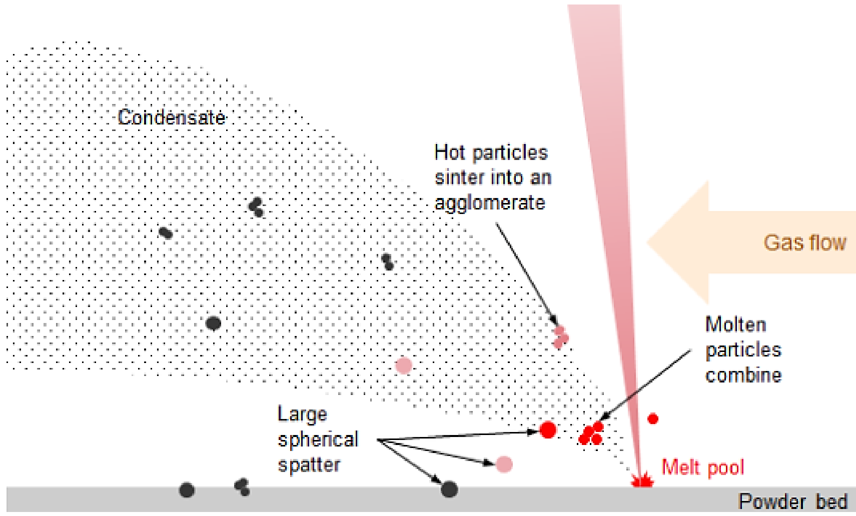


Figure 4: Condensate Generation

Once collected, dry condensate runs the risk of combustion (particularly titanium and aluminum powder waste), and proper passivation is vital before transport per EPA requirements. Silicone oil is a preferred material since it has a higher flash point threshold compared to mineral oil. Flocculants such as chalk or sand are also recommended by the manufacturer to encapsulate the condensate and prevent possibility of oxidation that may lead to combustion.

Lab Sampling Procedures and Testing

Once waste condensate has been generated by an additive manufacturer, it must be analyzed by an accredited third-party lab to determine chemical composition and potential hazardous components. Every U.S. state has individual requirements for its testing facilities. They must be substantiated by local departments of health to obtain permits, certifications, and accreditations. The waste generator, lab technicians, and waste disposal company work jointly to form a waste profile describing the components of each waste stream. An accurate waste profile is required by the EPA and USDOT before transportation. These samples can either be composite samples (multiple samples taken at regular intervals over a period) or a grab sample (one time sample taken at singular point for collection) and should be stored in a preserved or unpreserved container. Preserved containers are preferred for materials or chemicals that may evaporate or have a reaction with oxygen such as the condensate.

Routine chemical analysis tests like toxicity characteristic leaching procedure areused to determine whether there are hazardous elements present in the waste sample. The test entails a leaching simulation and reveals any negative health hazard results. Other instruments used for testing include gas chromatography, mass spectrometry, inductively coupled plasma, x- ray fluorescence, optical emissions spectroscopy, and a mercury analyzer.

A separate test is required to determine ignitability, based temperature conditions and burn rates. As discussed, some metal powders such as, but not limited to, aluminum and titanium may "flash" when subjected to high temperatures during analysis. If a substance flashes, it must be disposed at an official incineration facility. Depending on the hazardous material concentration in the full chemical analysis, the material may have to be neutralized by an inert agent before transportation.

Disposal is based on all the information discussed above. Once all factors are determined, options for disposal may include beneficial reuse, recycling, waste to energy, treatment/stabilization for landfill, or incineration. Often times, a sample will need to be shipped for benchmark testing at the end disposal site before final approval.

Figure 5: Analytical Instruments for Hazardous Waste Lab Testing

Case Study: Sintavia, LLC

Based in Hollywood, Florida, Sintavia, LLC designs and prints (via the PBF process) complex, mostly thermodynamic components for the Aerospace, Defense, and Space industry. They were the firstindependent manufacturer of their kind to offer a vertically integrated, end-to-end metal additive design and manufacturing production process that met aerospace production quality standards with respect to these parts. The company is Nadcap and ISO/IEC 17025 accredited, AS9100/9110 certified, and ISO 14001 certified. Currently, Sintavia utilizes 28 PBF printers and plans to add two to three more in 2021, and eight to ten again in 2022. They have a state-of-the-art quality and metrology department as well as a full-scale machine shop for post processing. The majority of the company’s printers are from EOS GmbH.

Currently at Sintavia, condensate is handled and disposed of per standards set forth by the EPA, Florida Department of Environmental Protection (FDEP), and Florida Department of Transportation (FDOT). These standards are adhered to at the highest level when working with condensate. While using a wet separator vacuum, condensate is recommended to be neutralized by water or oil with organic additives. For dry condensate within the machine, argon gas is utilized to prevent any oxidation/reaction of the powder during exposure. From the printer, dry condensate is then transferred into an airtight particle bin promptly filled with sand and silicone oil as the neutralizing agents.

Figure 6: EOS AM Machines at Sintavia

With respect to the analysis of condensate, Sintavia uses internal and external lab resources to perform any necessary testing. Following respective sampling procedures, possible analytical could include TCLP, mercury analysis, and ignitability.

Figure 7: In House Laboratory at Sintavia

Transportation and disposal of hazardous materials are regulated monthly between the environmental, health, and safety engineer and Triumvirate Environmental, Sintavia's hazardous waste removal partner. Regardless of waste stream, however, Sintavia is aware of—and remains liable for—the appropriate disposal of each type of condensate.

According to Ashley Wallace, Sintavia's Quality & EHS Engineer, knowing where each condensate stream is going is just as important as the careful preparation of each type of waste. "As we have grown, we have recognized that proper disposal of all of our waste streams must be a priority. We have worked with Triumvirate Environmental and other experts within the industry to manage the final disposal of these streams according to all regulatory requirements." The ultimate goal is to find beneficial reuse or recycling options, which will continue to become more available as technology advances. The company's main waste streams are disposed of in the following manner:

- Aluminum alloy condensate is considered ignitable, and is therefore deemed hazardous waste. It is sent to an incineration plant in Ohio.

- Nickel and stainless-steel alloy condensate contains chromium content above the EPA's 5ppm limit; therefore, it is categorized as hazardous waste. This material is recyclable and current strategies, such as metal recovery, are under development. For now, this waste is solidified and disposed of in an underground facility in Canada.
- Titanium alloy condensate is non-ignitable with no chromium content; therefore, it is classified as regulated, non-hazardous waste. This material is recyclable and current strategies, such as metal recovery, are under development. For now, this waste is transported to a waste energy facility in Georgia.
- Wet condensate from the wet-vacuum is considered hazardous due to chromium contentabove 5 ppm. It is solidified and disposed of at an approved landfill in Kentucky.
- Industrial wastewater is considered non-hazardous. It is sent to a wastewater treatment facility in South Florida.

These waste streams are disposed of in conjunction with manufacturer guidelines and disposal company recommendations.

Summary

As PBF manufacturing and the AM industry continue to grow and expand, so will the importance of disposing of condensate waste in a safe and efficient manner. While waste streams generated by PBF represent a small fraction when compared to similar traditional manufacturing processes, correct disposal of condensate remains a critical aspect of the underlying environmental benefits of PBF. In addition, research is currently being performed on recycling alternatives for metal condensate, which would assist in reducing this waste. For now, however, respectable disposal of condensate waste remains a priority for the growing industry. Awareness of and compliance with the EPA's regulations are essential for the long-term success of the PBF AM industry.

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