

Environmental aspects of laser-based and conventional tool and die manufacturing

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Abstract

Solid Freeform Fabrication (SFF) technologies such as Direct Metal Deposition (DMD) have made it possible to eliminate environmentally polluting supply chain activities in the tooling industry and to repair and remanufacture valuable tools and dies. In this article, we investigate three case studies to reveal the extent to which DMD-based manufacturing of molds and dies can currently achieve reduced environmental emissions and energy consumption relative to conventional manufacturing pathways. It is shown that DMD's greatest opportunity to reduce the environmental impact of tool and die manufacturing will come from its ability to enable remanufacturing. Laser-based remanufacturing of tooling is shown to reduce cost and environmental impact simultaneously, especially as the scale of the tool increases.

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1. Introduction

The forming and shaping of metals and plastics, via processes such as injection molding, stamping, and forging, are essential to modern society. Tools, dies, and molds, collectively referred to here as “tooling,” are required to produce nearly all plastic and metal products in industries such as automotive, medical, aerospace, and consumer electronics. Nevertheless, tooling production is a time consuming, technically difficult, and expensive production process that requires specialized materials, labor, and manufacturing techniques. The challenge associated with tooling production is in part reflected by the fact that lead times required to produce tooling average 11 weeks, with large, complicated tools such as those in the automotive industry often requiring lead times in excess of one year [1]. Despite the expense and difficulty of designing and manufacturing tooling, dies and molds often have limited

in-service lifetimes due to harsh use conditions including large loads under elevated temperatures, thermal cycling, repeated/reversed loading conditions, contact with corrosive materials, and continuous production schedules. The increasing pace of new product development, claimed to be the greatest driver for the production of new tooling [1], shortens the service lifetime of tooling further by making tooling obsolete prior to functional failure.

Solutions to the technical challenges of tooling production are currently being sought against significant changes in the U.S. manufacturing industry. Specifically, large U.S. manufacturing facilities are currently relocating to foreign countries to take advantage of low labor and manufacturing costs. Manufacturers are more likely to purchase tooling locally, compounding the cost disadvantage U.S. tooling providers face relative to foreign competition. Although the U.S. currently maintains a leadership position in high precision, high accuracy tooling, over time it can be expected that this leadership position will erode as foreign manufacturers become more highly skilled.

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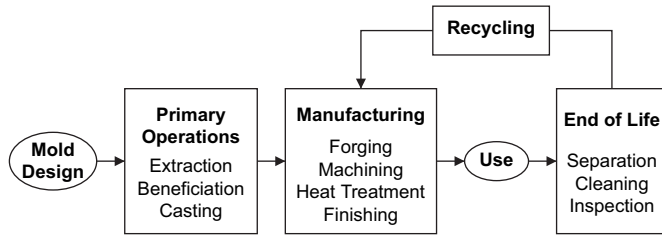


Fig. 1. Major components of the tooling life cycle.

These economic challenges exist in the midst of rising awareness of the environmental impacts within the industry and against the flux of tooling production towards countries with less stringent environmental standards. The tooling life cycle (Fig. 1) is not environmentally sustainable for a number of reasons, including the consumption of limited material and energy resources and the pollution of terrestrial, aquatic, and atmospheric systems during production and utilization activities. The manufacturing operations generating these impacts include casting, forging, and machining, operations which, according to the U.S. Environmental Protection Agency [2], release a significant percentage of the nation's greenhouse gases, consume large amounts of limited natural resources, are among the most significant polluters of freshwater systems, and are responsible for the release of particulates, metal oxide fumes, and respirable organics that are harmful to human health. In addition to material, energy, and associated emissions listed in Table 1, pollution in the tooling production cycle can be attributed to “engineered scrap” operations such as machining that removes metal previously invested in the life cycle of the tool, and ancillary products and materials (e.g., hydraulic oils, cutting fluids, casting sand, cutting tools, etc.) that are necessary to achieve economical tooling production but that are not part of the final tool itself. These externalities of production are significant inhibitors to the goals of environmentally benign manufacturing, creating opportunities for cleaner production and progress towards sustainability.

For these reasons, additive net-shape Solid Freeform Fabrication¹ (SFF) operations were highlighted at the September 2001 Workshop on Environmentally Benign Manufacturing (EBM) for their potential to reduce environmental impact within the metals manufacturing industry [3]. In contrast to metal removal operations conventionally used in the tooling industry, an additive process creates a mold or die cavity by “building the boundary” instead of removing cavity material from a bounding volume (Fig. 2A). By utilizing only the amount of material needed for the product, additive manufacturing technologies have the potential to reduce the life cycle material mass and energy consumed relative to conventional subtractive techniques by eliminating engineered scrap, while also eliminating the use of harmful ancillary process inputs.

Certain SFF techniques also have the capability to completely eliminate supply chain operations associated with the production of new tooling by their capability to enable repair

¹ Also called Layered Manufacturing (LM) and Rapid Prototyping (RP) technology.

Table 1

Tooling supply chain manufacturing operations and associated environmental impacts

Process	Opportunities for reduced environmental burden
Casting	Air/water emissions and energy consumption from furnace and mold material handling operations; solid waste from discarded mold material; general footprint of factory operation and associated overhead.
Forging	Energy consumption; hydraulic fluid use and spills; conversion coating use; metalworking lubricants and fluids; footprint/overhead; tool production and disposal.
Machining	Energy consumption; production and handling of waste chips; metalworking fluids; tool production and use; on-site wastewater treatment.

and remanufacturing of obsolete or failed tooling. A variety of industrial sectors have found remanufacturing of existing products, in lieu of original production, a successful approach to simultaneously reduce costs, increase productivity, and reduce environmental impacts. While it has been estimated that such remanufacturing activities account for \$56 billion of the U.S. economy per annum [4], remanufacturing of tooling is rarely performed. This is because currently used techniques such as welding cannot restore metal microstructures to “as-new” condition when the tool fails or a design change occurs. However, recent scientific and engineering advances in laser-based metal freeform fabrication have put tooling remanufacture within the reach of technological and economic feasibility. For the tooling industry, remanufacturing enabled by certain SFF techniques provides an excellent opportunity to increase industrial competitiveness by reducing tooling costs and lead times relative to original production. By eliminating polluting steps in the supply chain for new tooling production via remanufacturing, SFF offers an opportunity to increase industrial competitiveness while reducing environmental impacts.

This paper considers the conditions under which a particular instantiation of SFF, Direct Metal Deposition (DMD), can be considered environmentally superior to the conventional manufacturing of tooling. Three case studies are investigated: (A) a simple injection mold insert, (B) a mirror fixture designed for use in outer space, and (C) a stamping die used in the auto industry. These cases are chosen to highlight situations where conventional or laser-based tooling production pathways may hold environmental advantages. Based on these case studies, a number of general observations are raised regarding environmental aspects to be considered in the technological choice between conventional manufacturing and SFF for tooling production.

The paper proceeds as follows: Section 2 provides background on SFF and DMD technologies, including environmental issues to be considered. Section 3 presents an overview of the three case studies investigated in this research. Section 4 compares the life cycle activities associated with tooling produced by SFF and conventional manufacturing. Section 5 describes the specific case study results. Sections 6 and 7 offer discussion and conclusions.

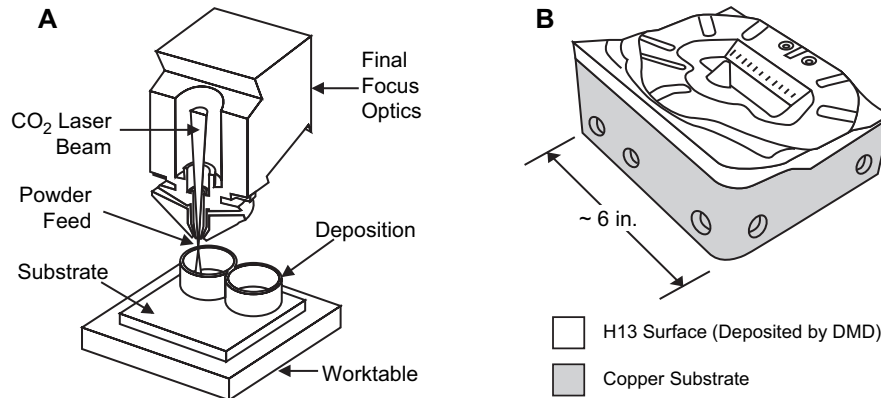


Fig. 2. (A) Direct Metal Deposition (DMD) technology; (B) mixed-material mold: H13 tool steel deposited on a copper substrate using the DMD process.

2. Solid Freeform Fabrication technologies

Table 2 lists a selection of currently available metal SFF techniques along with a comparison of their processing characteristics. Each of these techniques is appropriate for tooling production, and three (SLS, 3DP, and DMD) have already been commercialized [6,9,10,19]. The technique chosen for this investigation, Direct Metal Deposition (Fig. 2A), is an SFF process that integrates five technologies already common to manufacturing: high-power lasers, Computer Numerical Control (CNC), Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Powder Metallurgy (P/M) [14–19]. Similar to other metal freeform fabrication technologies, DMD is an additive process whereby CAD models are sliced into thin layers, then built layer-by-layer using the laser to melt a stream of powdered metal that deposits onto a substrate. The key characteristic differentiating Direct Metal Deposition (DMD) from other SFF technologies capable of producing metal parts is its use of closed-loop feedback control to achieve high dimensional resolution. Moreover, the characteristically rapid cooling of DMD results in a fine material microstructure as is necessary for tooling applications [14,17]. It has been shown that DMD tooling can be manufactured to near-final dimensions in a single step from commercially available tool material powders resulting in

tooling with production-quality mechanical and metallurgical properties.

Laser-based metal deposition techniques such as DMD are, in principle, net-shape manufacturing processes, being able to build objects to near-final dimensions from metal powders and electricity without creating engineered scrap [12–14]. As a net-shape process, and because of the ability of the technology to use existing tooling as a process input, the use of DMD as a die and mold manufacturing process has the potential to reduce or eliminate conventional supply chain operations such as casting, forging, and machining, subsequently reducing product lead times as well as the fossil fuel consumption, pollution, and resource wastes listed in Table 1.

There are additional advantages to the application of DMD in tooling production. First, reduced manufacturing complexity can lead to shorter time-to-market for metal tooling. It has been estimated by POM Group Inc. (Auburn Hills, MI) that DMD can reduce tooling lead times by 35% as compared with conventional processes. This 2–3 week acceleration in mold production would enable an additional product cycle per year for highly competitive industries such as toy and shoe molds. While this makes the DMD process route highly productive, it also makes the technology a candidate for the rebound effect, possibly offsetting any environmental gains achieved from the alternative production route.

Table 2
Solid Freeform Fabrication (SFF) techniques, relevant characteristics, and references

Technique name	Abbreviation	Raw material	Principle energy input device	Additional processing conditions	Multi-material ^a	References
Selective Laser Sintering	SLS	Metal powder (heated)	CO ₂ /Nd:YAG laser	Inert gas chamber, heated powder, pressing ^b	No	[5,6]
3-Dimensional Printing	3DP	Metal powder, binder	Furnace	Pressing, sintering ^b	No	[7–10]
Light Engineered Net Shaping	LENS	Metal powder	Nd:YAG laser	Inert gas chamber	Yes	[11]
Direct Light Fabrication	DLF	Metal powder	Nd:YAG laser	Inert gas chamber, heat treatment	N/A	[12,13]
Direct Metal Deposition	DMD	Metal powder	CO ₂ /Nd:YAG laser	Inert gas delivery, stress relief	Yes	[14–19]

^a Multi-material: capability of the process to deposit multiple materials “on-the-fly” during processing, i.e., switching deposited material on demand without process flow interruption.

^b Hot/cold isotactic pressing: some processes require compaction of the “green” shape created by binding or partially fusing metal powder and further furnace treatment to increase density or replace binder with a second metal phase.

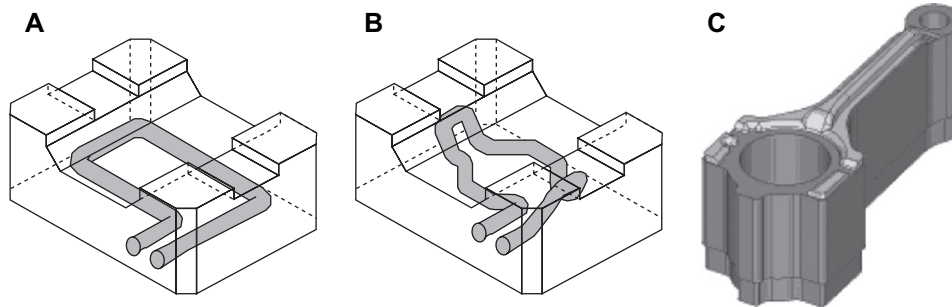


Fig. 3. (A) Conventional cooling channels; (B) Conformal Cooling Channels (CCC); (C) wear-resistant coating (shaded grey) as to be applied to a tool blank.

Secondly, it has been shown that the tool illustrated in Fig. 2B (steel deposited on copper substrate) can reduce per-unit injection molding cycle times by upwards of 25% relative to conventional single-material tool steel molds due to heat transfer improvements arising from the use of a copper substrate [16]. Mixing of materials in order to improve mold thermal conductivity is here termed an Integrated Mixed-Alloy Heat Sink (iMAHS), which can be considered an instantiation of the broader category of Functionally Graded Materials [8,18].

Similar use-phase productivity gains to those observed in the case of iMAHS technology can be achieved in the injection molding process by using Conformal Cooling Channels (CCCs) which wrap around the contours of a mold cavity as shown in Fig. 3B, [9,10,19,20]. CCCs that are enabled exclusively by SFF techniques reduce the distance between the cavity surface and the cooling channels, which creates a more uniform cooling profile than can be achieved by the straight cooling channels conventionally produced by drilling (Fig. 3A). Economic benefits from cycle time reductions have already put CCCs into commercial application [9,10,19]. In comparison to the iMAHS route, CCCs avoid the need to utilize environmentally intensive metals (e.g., copper) along with the need to mix materials that are incompatible from the recycling perspective (e.g., copper and steel). While environmentally preferable, the CCC approach is considerably more challenging from the standpoint of mold design and process planning.

A third advantage of using DMD to produce tooling is the opportunity to deposit wear-resistant alloys onto tool surfaces that can lead to a significant extension of useful life for metal

tooling. Fig. 3C illustrates an example of a wear-resistant coating applied to a forging tool via DMD for connecting rods in mass-produced powertrain components. The universal application of these coatings would, by avoiding the production of new tooling, reduce the environmental emissions and consumption of non-renewable materials and energy considerably.

While eliminating the processes listed in Table 1 through the use of DMD would have a positive impact on the environmental profile of tool manufacturing activities, DMD technology itself is energy intensive relative to conventional subtractive manufacturing operations such as milling. Even at a theoretical level, it takes less energy to create new surfaces in shear than to melt and solidify: specific energy for metal cutting can be an order of magnitude less than the specific energy of melting metals such as those utilized in the tooling industry [21]. Thus, the trade-offs that exist between process-specific and supply chain environmental burden, technical advantages in use, rebound effects, and available options at End of Life (EoL) must be comprehensively examined when considering SFF as a potentially cleaner production alternative to conventional tooling manufacture.

3. Overview of case studies

3.1. Case Study A: injection mold insert

Case Study A considers a standard cavity insert plate for an injection mold tool, as shown in Fig. 4A. This design was chosen so that the initial case would have a simple and direct manufacturing process, through both conventional and DMD

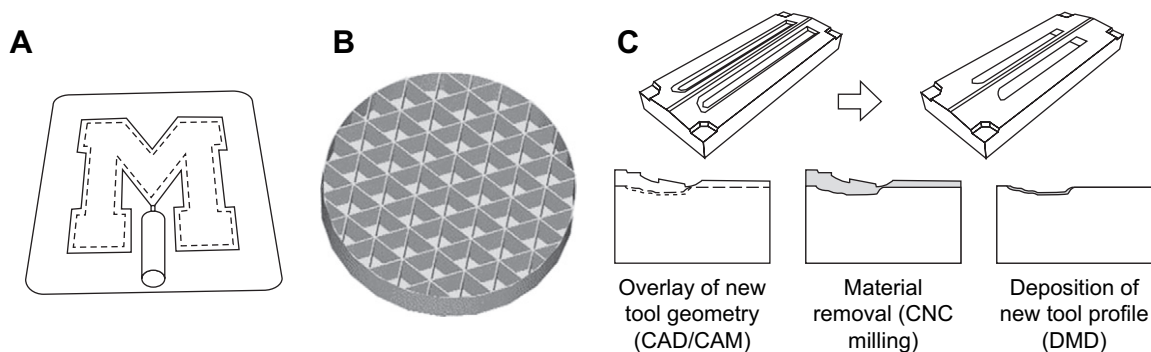


Fig. 4. (A) Case Study A mold insert design; (B) Case Study B mirror design; (C) Case Study C remanufacturing case (top) with manufacturing steps (bottom).

pathways. The insert was produced via DMD at The University of Michigan and via CNC milling by a contracted tooling provider. Energy consumption and other process effluents were directly measured or calculated for both manufacturing process routes. These data are applied in *Case Studies B* and *C* to predict the life cycle energy consumption and emissions of DMD and CNC milling process routes for producing tooling.

3.2. Case Study B: mirror fixture

The goal of *Case Study B* was to explore the influence of decreasing “solid-to-cavity volume ratio” on the relative energy consumption of products produced by CNC milling versus DMD. The solid-to-cavity volume ratio is defined as the ratio of the solid mass of the tool to the total mass of the minimally bounding volume of the tool assuming it were completely solid and made of the same material as the tool. *Case Study B* (Fig. 4B) involves the study of a lightweight mirror designed for an application in outer space. The mirror is a thin-walled structure that was deposited on the back of a stainless steel surface and polished to a surface finish of 40Å.

3.3. Case Study C: remanufactured tooling

Case Study C investigates the degree to which DMD-based remanufacturing can reduce energy consumption and emissions relative to the production of new tooling. In this case study, which was conducted in cooperation with POM Group Inc., the reconfiguration of a large-scale stamping die utilized by a leading U.S. company is considered. As shown in Fig. 4C, the case study involved the conversion of a 2002 model prototype tool into a 2003 model prototype tool by minimal (1.5 mm) surface additions on a small area of the tool surface. The changes included the relocation of the vehicle’s logo, which is an example of a case where a relatively minor design change can require the production of new tooling at significant cost to the manufacturer and the environment.

4. Life cycle energy and emissions associated with DMD versus CNC milling

The case studies defined above have been constructed so that a simple comparison can be made between DMD and the most basic operation in conventional tooling manufacturing: CNC milling. This section describes the differences in the life cycle activities associated with producing tooling via CNC milling versus DMD. Section 4.1 describes the differences in material production energy and emissions when producing tool steel plate as input to the CNC process route versus tool steel powder as input to the DMD process route. Section 4.2 lists the energy consumption and process emissions for DMD and CNC milling under the experimental conditions of *Case Study A*. Results are presented as energy consumption and emissions per kilogram of material deposited (DMD) or removed (CNC milling). Section 4.3 describes the potential for environmental differences during the use-phase

and End of Life (EoL) of tooling as it is influenced by selecting DMD versus CNC milling as the tooling production route.

4.1. Material production emissions and energy consumption

For all case studies, AISI type H13 tool steel plate or powder is utilized as the tool material. H13 is ubiquitous in the tooling industry and is appropriate for the production of tooling via forging, forming, and metal cutting operations [21,22]. Additionally, H13 has been studied extensively in previous DMD investigations [14,17].

4.1.1. Tool steel plate production for CNC milling

Tool steels such as H13 are produced via an Electric Arc Furnace (EAF) route, schematically represented in Fig. 5A [22–25]. Typically, a batch of 75% scrap and 15% pig or sponge iron is processed and cast into ingots [22], suggesting that recycling is essential to the technical and economic success of the process. The melted charge of scrap steel and iron is purified to exact composition through ladle refining, remelting, and recasting steps [22–25]. The ingots are heat treated and then processed into blocks, plates, slabs, or rounds through forging and rolling operations, with preheating performed as necessary [24,25].

Specific Energy Consumption² (SEC) and emissions coefficients for CO₂, SO_x, NO_x, CO, and airborne PM, compiled for the U.S. Department of Energy and broken down by production task in Table 3, were applied to approximate the energy consumption and emissions arising from the production of tool steel [26]. These data are comparable with other studies available in the literature [28–30], and were selected due to a greater depth of description and the joint listing of energy consumption with emissions’ data. Since energy consumption and emissions’ data for H13 tool steel production are not known by the authors to be in the publicly available literature, it is assumed here that a single remelting step is undertaken for H13 tool steel with energy consumption and emissions approximately equal to EAF melting as listed in Table 3. Based on the conclusions of Ref. [26], it is assumed that the relative environmental impacts of water discharges from EAF melting are negligible relative to air emissions. It is also noted that the solid waste from the process known as “EAF dust” is classified as a hazardous waste [26].

4.1.2. Tool steel powder production for DMD

Metal powders are commonly produced by water- or gas-atomization [31–33]. In the atomization process, a cross-stream of high-velocity water or gas is impinged upon a flow of molten metal, creating droplets that solidify into spherical particles. For the case of H13, diatomic Nitrogen (N₂) is utilized to achieve spherical particles that are roughly 150 μm in diameter [17,31]. The atomization process requires sufficient energy input to break up a stream of molten metal [31]. The SEC

² “Specific Energy Consumption” is also commonly referred to as “Energy Intensity.”

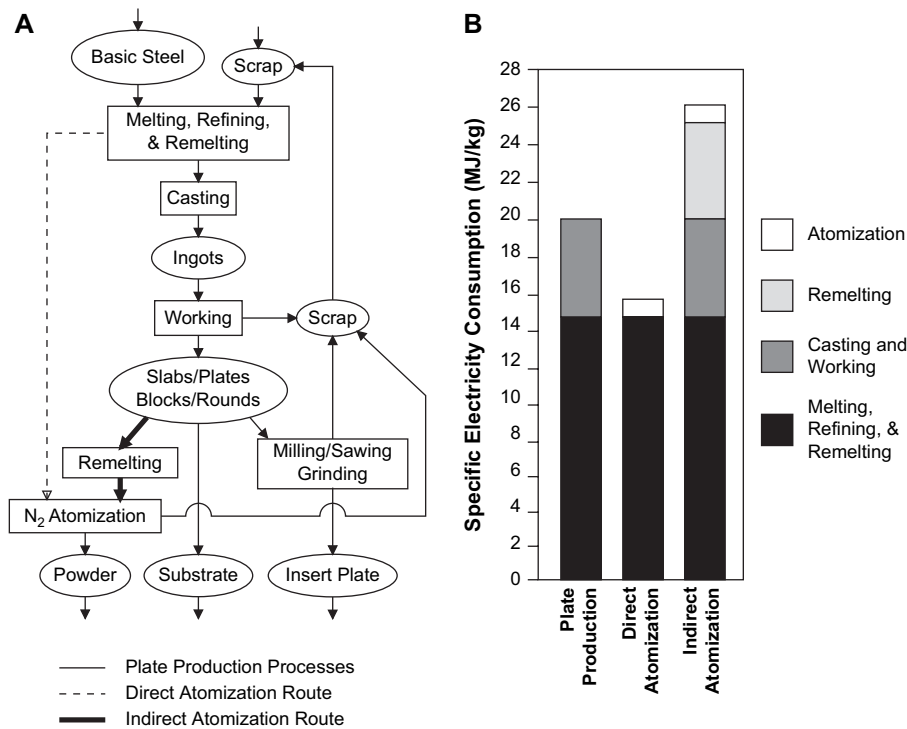


Fig. 5. (A) Raw material production processes for DMD (powder) and conventional manufacturing (plate); (B) Specific Energy Consumption (SEC) of material production pathways.

for the atomization of tool steels, isolated from melting operations, has been estimated to be on the order of 1 MJ/kg [31]. The only published emissions' data for atomization known to the authors are summarized in Table 3, [34,35]. While it is possible to produce powder directly from molten steel (i.e., without casting, forging, and rolling into a final product), such a "direct" process route is not always taken. Alternatively, an "indirect" process route may be taken where powder is produced from finished metal slabs or plates as illustrated in Fig. 5A.

4.1.3. Comparison of tool steel powder versus plate

Fig. 5B compares the energy consumption associated with the production of H13 steel plates versus H13 steel powder for both direct and indirect atomization routes. It is observed that relative to the production of steel plate (20 MJ/kg), the direct atomization route to producing steel powder requires approximately 20% less energy per kilogram of produced powder while the indirect atomization route to producing steel powder requires approximately 25% more energy. With respect to air emissions per kilogram of material produced, the direct atomization route results in less CO₂, SO_x, NO_x, CO and particulate matter than steel plate production with percent reductions ranging from 3% to 27%. The results illustrate potentially significant energy and environmental advantages to the production of tool steel powder versus tool steel plate.

Although tool steel powder via the direct atomization route has fewer environmental emissions, it is important to note that the in-process powder utilization percentage can be relatively low. For DMD in Case Study A, the powder utilization percentage (i.e., the percentage of powder mass input to the system

that actually becomes fabricated product) was observed to be about 8%. However, the physical barriers (e.g., oxidation) to direct reuse of powder are easily overcome for tooling materials, which means that unused powder can typically be reused directly in the DMD process. In practice, direct reuse can lead to nearly 100% powder utilization.

4.2. Manufacturing process energy consumption and emissions: DMD and CNC milling

Any potential gains associated with producing tool steel powder for DMD in place of tool steel plate for CNC milling must be considered in light of the manufacturing processes themselves. Even for a single operation such as DMD and CNC milling, the operating parameters and emissions can vary significantly. Therefore, Case Study A is utilized to select reference operating conditions that are applied to Case Studies B and C.

4.2.1. CNC milling pathway

The scope of this investigation for the CNC milling pathway is illustrated in Fig. 6A. For large tools, steel is generally cast to near net-shape ("precasting") and then finished using metal cutting processes. For smaller tools, such as that investigated in Case Study A (Fig. 4A), standard plates are sawed to rough shape from rolled slabs and then milled to tolerated geometry [1,9,36–38]. The patterns which form the final part geometry within these insert plates are usually produced via CNC milling and/or Electrical Discharge Machining (EDM) [1,36–38]. CNC milling is economically

Table 3
Specific Energy Consumption (SEC) and emissions of criteria air pollutants for operations involved in the production of raw material tool steel

Process	Energy (MJ/kg)		Airborne emissions (g/kg) ^a				
	Elec.	Other ^b	CO ₂	SO _x	NO _x	CO	PM ^c
Basic steel ^d	18.80	—	2667	1.07	0.53	0.20	0.27
EAF production	5.45	0.80	1012	3.32	1.27	0.41	0.92
Ladle refining ^c	1.15	0.12	141	0.70	0.27	0.09	0.19
Remelting ^f	5.45	0.80	1012	3.32	1.27	0.41	0.92
Ingot casting	1.87	1.44	—	1.14	0.52	0.16	0.32
Reheat furnace	0.00	1.87	— ^h	0.58	0.33	0.10	0.16
Hot rolling	1.33	0.12	282	—	—	—	—
Cold rolling	1.15	0.00	129	0.65	0.30	0.09	0.18
Annealing	1.19	—	— ⁱ	—	—	—	—
Atomization ^g	1.00	0.00	145 ^j	0.03	1.00	—	0.34
Plate production	20.41	5.15	2976	9.87	4.04	1.29	2.73
Direct powder production	15.9	1.72	2710	7.53	3.89	0.94	2.41
CNC milling: roughing cuts	24	—	6072 ^k	33.6 ^l	9.6 ^m	—	—
CNC milling: finishing cuts	600	—	151,800 ^k	840 ^l	240 ^m	—	—
Deposition (DMD)	7708	—	1,950,124 ^k	10,791.2 ^l	3083.2 ^m	—	—

Unless otherwise referenced, data are from Ref. [26].

^a All including emissions from electricity generation.

^b Includes fuel oil, natural gas, oxygen, carbon.

^c PM: listed as “Dust” in Ref. [34], provided as particulate matter in Ref. [26], both as airborne emissions.

^d Although these values are for 1 kg basic steel, note that roughly 0.15 kg basic steel is used to produce 1 kg of EAF steels.

^e “Vacuum Degassing and Ladle Refining” processes [26].

^f Assumed equal to EAF production step.

^g Data from Ref. [31].

^h Included in “Hot Rolling”.

ⁱ Included in “Cold Rolling”.

^j Using an emissions coefficient of 145 g CO₂/MJ (approximately 503 kg CO₂/MWh) as applied in Ref. [26].

^k Emissions coefficient for CO₂, 253 g CO₂/MJ (909 kg CO₂/MWh) for Midwest Grid [27].

^l Emissions coefficient for SO₂, 1.4 g SO₂/MJ (9 kg SO₂/MWh) for Midwest Grid [27].

^m Emissions coefficient for NO_x, 0.4 g NO_x/MJ (1.5 kg NO_x/MWh) for Midwest Grid [27].

advantageous, but has reduced accuracy and poorer surface finish than EDM. EDM is characterized by high accuracy and excellent surface finish, but has drawbacks associated with slow material removal rates, large lead times, and high costs associated with the necessary production of multiple job-specific graphite or copper electrodes [21,36]. EDM, which is not considered in these case studies, is of particular environmental relevance due to (1) large electrical requirements, (2) process dielectrics that can become hazardous waste, and (3) environmentally intensive and highly specific graphite or copper tools (“electrodes”) that wear quickly.

CNC milling of tool steels requires cutting tools that are strong, precise, and expensive, involving specialty steels and ceramics that are commonly coated to improve wear characteristics [36]. Typically, H13 tool production via CNC milling will also require cutting fluids and heat treatments (although they were not required for *Case Study A*). In this investigation, the environmental emissions associated with cutting tools, fluids, and heat treatments used in the CNC milling process were not considered. Possible implications of these factors in the analysis are discussed in Section 6.

In *Case Study A*, the insert design of Fig. 4A was cut from a 3.5" × 3.5" × 1.25" block of H13 tool steel. A photo of the insert as produced is shown in Fig. 7B. Fig. 7 lists the five milling steps required to produce the insert, and Fig. 8 provides the spindle speed, machining time, mean power, and total

electricity consumption for each step. The five machining steps took 55 min in total and consumed 8 MJ of electricity. The electricity consumption shown in Fig. 8D includes the spindle drive, worktable, and control system, as well as any inefficiencies in the machine tool. For each step, the observed power consumption exhibited little variation about the average value presented in Fig. 8.

Using the data in Fig. 8D, SEC values were calculated for “rough milling” (steps 1 and 2 in Fig. 8) and “finish milling” (steps 3–5 in Fig. 8). The distinction between “rough” and “finish” millings is particularly important given that a larger than expected disparity was observed between the SEC of rough milling (24 MJ/kg) versus finish milling (600 MJ/kg). This can be explained by the fact that finish milling requires increased spindle speeds, power draw, and operation times, along with decreased feeds and tool diameters, relative to rough milling. These factors all result in increased energy intensity per amount of material removed. In fact, 67% of the 4 MJ required in cavity milling was consumed in the finishing cuts, which represented less than 10% of the total cavity mass machined. It is also interesting to note that the observed SEC values differ greatly from milling data available in LCA databases. For instance, the SEC of milling has been reported as 0.4 MJ/kg, which is two to three orders of magnitude less than that observed here depending on whether rough versus finish milling is considered [39].

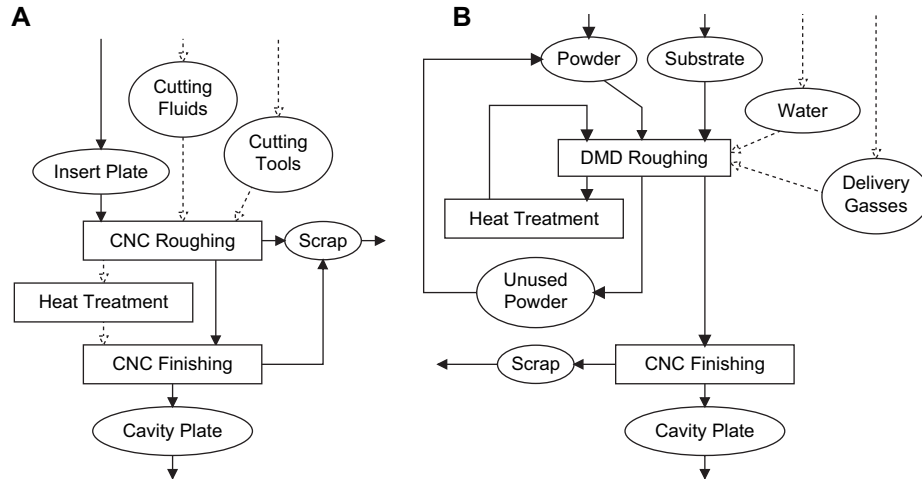


Fig. 6. Conventional and DMD cavity manufacturing operations considered in this investigation. Dotted lines indicate common activities not included in the assessment. (A) Conventional (CNC milling) cavity production; (B) DMD cavity production.

4.2.2. DMD pathway

In Fig. 6B, the scope of the DMD manufacturing pathway is illustrated alongside the conventional pathway. Generally, inert shield and delivery gases such as Argon (Ar), diatomic Nitrogen (N_2), and Helium (He) are used to facilitate powder flow and to resist powder oxidation during thermal processing. Inert gases and water are also used to cool the laser generator and the copper mirror array that directs the laser beam to its focal point (see Fig. 2). In DMD, HEPA filters are used to control the escape of metal powders and fumes. The HEPA filters are, at EoL, disposed off as hazardous solid waste. The spent filters are a low volume waste, disposed on average about once per year in the facility utilized in *Case Study A*. Direct particulate emissions escaping filtration, measured as concentration of hazardous particulate metals in the enclosed manufacturing environment, have been tested to be well below levels required by the U.S. Occupational Safety and Health Administration.

These ancillary inputs to the DMD process are relatively benign when compared with the ancillary inputs utilized in conventional manufacturing that are listed in Table 1, [13]. By far, the largest energy consumption and environmental emissions associated with DMD are derived from electricity consumption, meaning that practically all of the environmental

impact are determined by the amount of electricity required and the methods utilized to produce the electricity. In this case it was assumed that the “Average Midwest Grid” composition [27] was utilized to produce the electricity, leading to air emission results provided in Table 3.

A photo of the actual product produced during Case Study A is shown in Fig. 7C. For this case, a $3.5'' \times 3.5'' \times 0.5''$ plate of AISI type O2 tool steel was used as a substrate for the deposition of H13 tool steel. The total DMD processing time was 14.5 h, resulting in a total energy consumption of 3197 MJ. This accounts for the 6 kW CO_2 laser and all auxiliary equipment used by the DMD apparatus: a CNC worktable, chillers, powder feeder motors, and a computerized control system. The power consumption of the DMD process as a function of time is shown in Fig. 9A, where it is observed that the idle laser and cooling equipment were responsible for 29 kW of baseline electricity demand. It is also observed in Fig. 9A that the DMD power consumption was relatively steady about an average value of 61 kW, with maximum variations of approximately +3 and -10 kW.

The total energy consumption associated with material production and DMD manufacturing is shown in Fig. 9B. The DMD energy consumption value includes the energy required

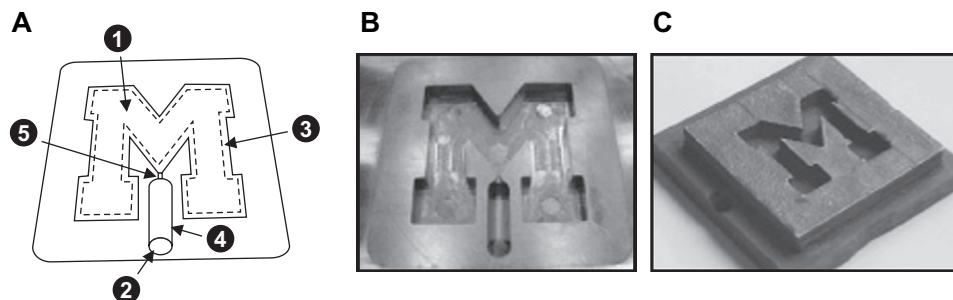


Fig. 7. (A) Detail of machining plan for the *Case Study A* insert: 1: roughing contour; 2: “Sprue puller” machining; 3: finishing contour; 4: “Runner” machining; 5: “Gate” machining; (B) *Case Study A* injection mold insert as produced via machining (post-finishing); (C) DMD fabricated insert (prior to finishing). The two bars appearing above steps 1, 3, and 4 are due to the use of two cutting tools and two distinct spindle speeds in undertaking these steps. Time, mean power, and energy for 1, 3, and 4 are the combined result of machining under these two settings.

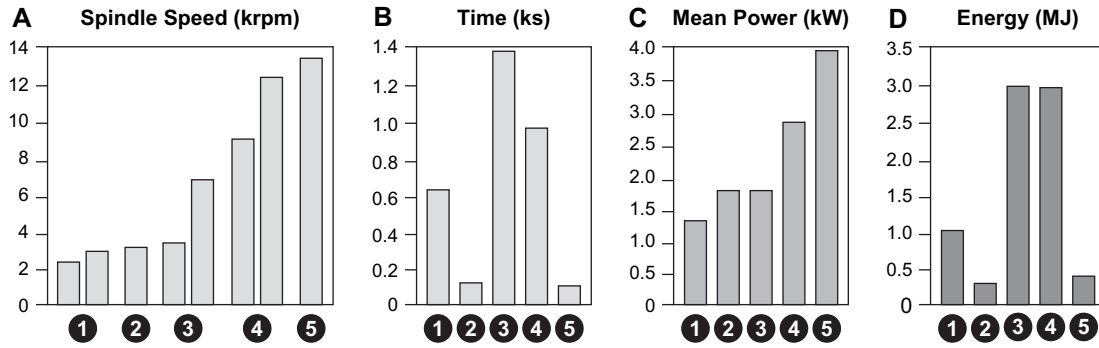


Fig. 8. Machining energy consumption in *Case Study A*. (Labels correspond to the notation introduced in Fig. 6.) (A) Spindle speed for the operation; (B) machining time; (C) mean power requirement; (D) cumulative (electrical) energy consumption for each operation.

for two stress relief heat treatments that were performed to prevent cracking of the tool [23]. These treatments were performed in a furnace rated at 13 kW, with the treatments each consisting of a heating period (3.5 h) followed by periods of soaking (4 h) and cooling (26 h). The total SEC calculated for the DMD process and heat treatments (7708 MJ/kg) was utilized for predictions discussed in *Case Studies B* and *C*.

4.3. Tooling use and End of Life

As discussed previously, additive SFF processes such as DMD have the capability to produce iMAHS (Fig. 2B) and CCC (Fig. 3B) molds that cannot be fabricated via CNC milling. In order to focus on an “apples-to-apples” technology comparison between DMD and CNC-based mold and die manufacturing, CCC and iMAHS technologies enabled by laser-based manufacturing were not directly investigated in this study. In the absence of CCC and iMAHS, it can be assumed that the energy consumption and environmental emissions associated with the use-phase are identical for tools created by DMD and CNC milling. This is because previous research in Refs. [14] and [17] has revealed that DMD-manufactured molds can produce parts of equal quality for

the same number of manufacturing cycles as conventionally produced tooling.

In the absence of iMAHS or CCC, it can also be assumed in *Case Studies A* and *B* that the EoL fate of a DMD-produced H13 tool is the same as a tool produced by CNC milling. In both the cases, the H13 tools enter a scrap stream to be recycled back into H13. In *Case Study C*, the ability to utilize DMD in combination with CNC milling to remanufacture tooling is considered.

5. Case study results and observations

5.1. Case Study A results

The relative energy consumption values for the CNC milling and DMD pathways are shown in Fig. 9B. It is observed that the energy consumption in the milling pathway is dominated by the process of producing tool steel plate while energy consumption in the DMD pathway is dominated by the manufacturing processes. In total, DMD consumes approximately 3 GJ more energy than CNC milling in the production of the insert. The higher life cycle energy consumption associated with DMD was expected since the solid-to-cavity ratio is

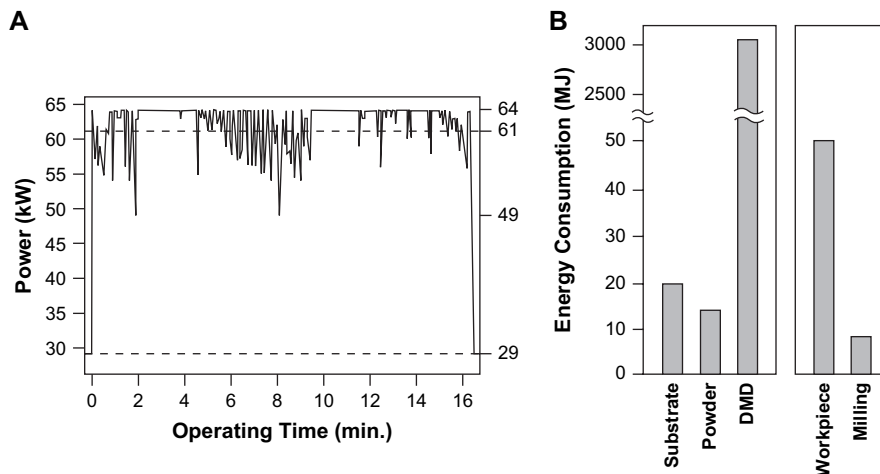


Fig. 9. (A) Representative DMD process energy consumption observation; (B) total energy consumption for *Case Study A* insert production via the DMD process pathway (left), against that for the milling pathway (right).

very large (>7). In contrast, the machining operation was relatively simple, requiring only 55 min of milling.

While simple cavities such as in *Case Study A* would always be produced via a conventional process pathway, this case study served well to calibrate prognostic energy consumption models for raw material production, milling, and DMD. The case study also revealed that when a sub-optimal DMD process is used, energy consumption can be rather high (e.g., 8 GJ/kg). The application of DMD was sub-optimal in *Case Study A* for the following reasons: (1) the DMD laser was not selected for minimal energy consumption (due to budget limitations), (2) the DMD process was not optimized for minimal overhead energy and powder consumption (see 29 kW background power in Fig. 9A), and (3) the material deposition rate was set at its lowest possible value. In fact, the material deposition rate (0.01 g/s) was at the minimum of DMD's capability (0.013–0.53 g/s for H13 [15]), which leads to a longer than necessary machine operation time and higher than necessary energy consumption. Usually, commercial production employs a deposition rate of 33–131 cm³/h with up to 5 kW of nominal laser power. Higher nominal laser power increases the deposition rate without proportionally scaling system's electricity consumption. These energy consumption issues have already been addressed in industrial practice, resulting in about an order of magnitude reduction in DMD's Specific Energy Consumption. Longer-term research into the use of less energy consuming lasers and more environmentally conscious energy sources would make DMD much more competitive in terms of energy consumption and emissions, even for simple products such as the one considered in *Case Study A*.

5.2. Case Study B results

While *Case Study A* investigated a case where the conventional pathway is the obvious choice for minimal energy consumption, *Case Study B* (Fig. 4B) is a case where DMD is the obvious choice for minimal energy consumption. This is a case where a thin-walled structure leads to a solid-to-cavity volume ratio of 0.33. As shown in Fig. 10, simulated manufacturing of the mirror fixture via CNC milling and DMD predicts less manufacturing time (4%) and energy consumption (80%) resulting from DMD. These predictions are based on the observations of *Case Study A* and would be magnified by considering increases in energy efficiency already possible for DMD.

5.3. Case Study C results

In *Case Study C*, DMD was used by POM Group (Auburn Hills, MI) to remanufacture a stamping tool for a leading U.S. truck manufacturer in association with a model year-end design change (Fig. 4C). In contrast to manufacturing a new tool “from scratch” as would ordinarily be done, the remanufacturing process only involved minor surface modifications which can be conservatively approximated as 10% of the original tool mass removed via CNC machining, 10% of the machined mass re-deposited using DMD, and 10% of the DMD-

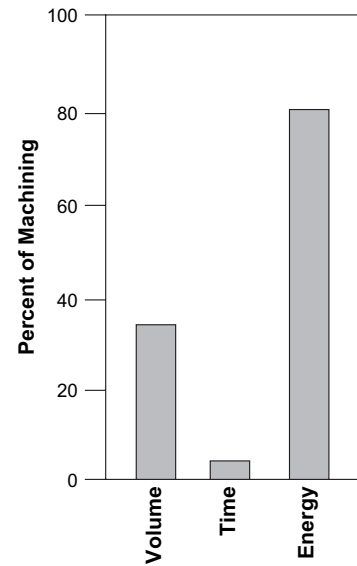


Fig. 10. Processing volume, time, and energy expenditure for DMD fabrication of the *Case Study B* mirror (Fig. 4B) as a percentage of the same for conventional manufacture (i.e., CNC milling).

deposited mass “finish” machined using CNC milling. These assumptions lead to Fig. 11, which indicates that while total remanufacturing energy consumption is not negligible (12 GJ), it is less than half of the energy consumption that would be expected just from producing the tool steel required for the new tool based on Fig. 5B. In this case, environmental savings are achieved at significant economic advantage: it was found in *Case Study C* that the remanufacturing process via DMD would save over \$250,000 during the life cycle of the tool.

6. Discussion

A comparison of *Case Studies A* and *B* reveals that the relative energy consumption of CNC versus DMD is driven by

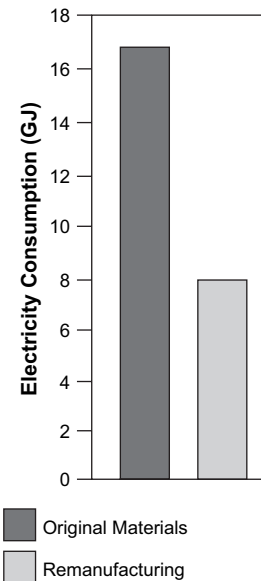


Fig. 11. Potential reductions in energy consumption through remanufacturing of the large-scale stamping tool shown in Fig. 4C.

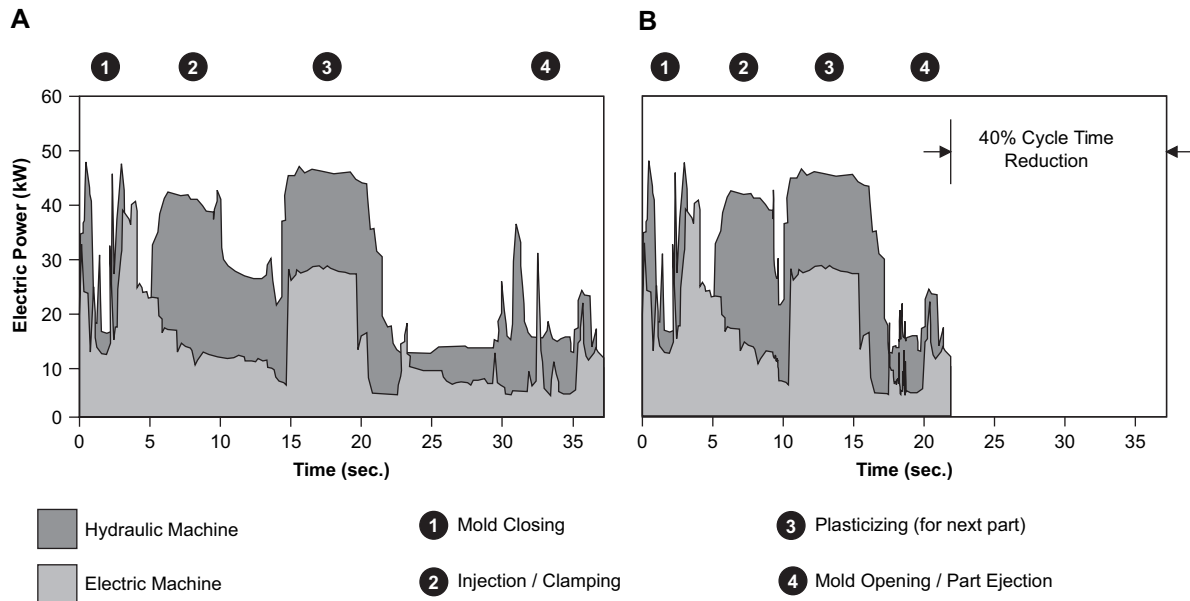


Fig. 12. (A) Prototypical injection molding cycle power consumption; (B) potential reductions in power consumption arising from cooling enhancements (CCC, iMAHS) giving a 40% reduction in cycle time.

the solid-to-cavity volume ratio. At low ratios, an additive DMD pathway minimizes energy consumption and emissions, while at high ratios the CNC milling pathway minimizes energy consumption and emissions. Although the process energy intensity for DMD was approximately three orders of magnitude greater than rough CNC milling, a number of factors make this difference less formidable than it would at first appear. To start, energy intensity in DMD was only one order of magnitude greater than finish machining. Energy efficiency improvements for DMD that close this gap already exist in the commercial implementation of the DMD technology.

Also, while the environmental emissions profile of DMD was almost entirely accounted for, a number of environmentally intensive components of the CNC milling process were not accounted for, such as cutting fluids, heat treatments, and cutting tool production. In particular, the environmental emissions associated with cutting tools used in this investigation were not considered due to absence of data relating to cutting tool production. However, it is known that typical tool coating processes such as Chemical Vapor Deposition or Physical Vapor Deposition are environmentally intensive. In fact, the electricity consumption required for vapor deposition of surface coatings onto high speed milling cutters alone may equal that required to mill the insert in *Case Study A* [40,41]. For operations featuring high rates of tool wear (e.g., *Case Studies B* and *C*) the relative contribution of tool production rises, and it becomes conceivable that tool production could become of even greater environmental significance than the actual machining process itself.

In addition, there is also potential for DMD to reduce the in-use energy consumption driven by the design of dies and molds. Previous research has revealed that through the use of CCC and iMAHS designs, injection molding cycle times can be reduced by 10–40%. Since typically about 50% of

energy consumption in a typical injection molding cycle is required for plasticizing [37], a 40% cycle time reduction corresponds to about a 20% energy consumption reduction, with the exact correspondence determined by the particular injection mold machine technology used (Fig. 12). However, any reductions raise the question of whether the inclusion of CCC or iMAHS can save more energy in the use-phase than the extra energy consumed by DMD in production. We expect, for simple injection mold tools such as *Case Study A* using CCC technology, that the 3 GJ excess spent in DMD mold manufacture could be regained through in-use energy savings for large part runs (over a million cycles). The breakeven point for iMAHS would be considerably longer than CCC due to recycling complications created by the mixing of incompatible metals (e.g., steel and copper) and the relative environmental intensity of copper production.

7. Conclusions

This research effort has produced a quantitative estimate of the energy consumption and emissions associated with the production of mold and die tooling via laser-based Direct Metal Deposition (DMD) and CNC milling. The research has revealed that complex trade-offs exist between the economic and environmental ramifications of alternative material production paths, manufacturing processes, and EoL options in the tooling industry. In particular, a detailed investigation of three case studies indicated that simple molds with high solid-to-cavity volume ratio and minimal amounts of finish machining are least environmentally burdensome to produce via CNC milling, while molds with a low solid-to-cavity volume ratio are least environmentally burdensome to produce via DMD. Rapid advancements in DMD and other Solid Freeform Fabrication technologies will necessitate frequent

re-evaluation of which process is least environmentally burdensome to apply for the production of a specific tool. However, regardless of how tooling is produced, the opportunity created by DMD to update, repair, and remanufacture tooling presents the possibility for large reductions in energy consumption, environmental emissions, and manufacturing costs.

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