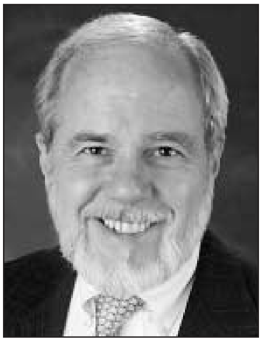
The new industrial revolution will enable people to live where they like and produce what they need locally.

The Transformation of Manufacturing in the 21st Century



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Manufacturing has been defined as the human transformation of materials from one form to another, more valuable form. The transformation can be geometric or compositional, or both. Manufacturing encompasses both the production of man-made materials originating from naturally occurring raw materials and the production of discrete parts, usually from those man-made materials. Nearly all discrete parts are made using a series of steps or processes that, with few exceptions, fall into one of four groups:

- *Casting or molding* produces an object by transforming a material from a liquid to a solid. A material in liquid form is poured or injected into a preformed mold (or die), allowed to solidify (normally by cooling, but sometimes by heating or chemical curing), and, once solidified, removed from the mold as a solid object. The mold is typically made from a metal with a higher melting temperature than the formed material. Sometimes the mold is disposable (e.g., sand or ceramic) and is destroyed during the removal of the formed part. In these cases, the mold itself is "molded" from a durable, preformed pattern.
- *Forming* is a process of applying force, and sometimes heat, to reshape, and sometimes cut, a ductile material by stamping, forging, extruding, or rolling. Like the tools used in casting or molding, the tools used in forming are preformed and durable.

- *Machining* is used to "cut" specific features into preformed blanks (e.g., slabs, bars, tubes, sheets, extrusions, castings, forgings, etc.) by manipulating a fast-moving cutting tool relative to the work piece on a special (usually computer-controlled) machine tool, such as a lathe, mill, or grinder. In the machining process, even though the cutting-tool material is considerably more durable than the work piece material, the tool is subject to wear and tear. Typically, many different tools are used, and a specific "cutter path" is programmed for each feature and each tool. Compensation is made for tool wear.
- *Joining* includes welding, brazing, and mechanical assembly of parts (made by molding, forming, or machining) to make more complex parts than would otherwise be possible with those methods. Typically, special fixtures or special tooling and programming of assembly machines or robots are used for each assembled part.

Manufacturers are constantly struggling to achieve an appropriate balance between scale and flexibility.

The common theme in the methods widely used to manufacture discrete parts is a significant up-front effort, which can take several forms: tooling (e.g., dies, molds, cutting tools); special-purpose machining; part-specific programming (e.g., tool selection, "feeds and speeds," cutter paths, tool wear compensation); and "design for manufacturing" (i.e., iterating product designs so that fewer, less expensive manufacturing operations are required to produce a product). To justify the up-front investment of time and money in planning, designing, tooling, buying, programming, installing, and proving out production lines and cells for making products, production volumes must be sufficient to amortize the investment at a reasonable cost per part. Manufacturers are constantly struggling to achieve an appropriate balance between scale and flexibility. "Just-in-time" manufacturing and "flexible manufacturing systems" are two of the best known strategies in that struggle.

The heart of the problem is that there are dozens, sometimes hundreds of steps in the production cycle—even for simple products—that require many different machines and worker skills. High-volume production scale unavoidably limits flexibility, and many machines and people must be gathered in one place to make many, many parts and products with limited variation. Even though individual steps in the production process have been dispersed in recent decades from the centralized, fully integrated factories of the 1950s into the "extended enterprise supply chains" of the 1990s (because the added cost of handling and shipping from component suppliers to assembly sites is outweighed by the flexibility of the supply chain and lower cost of labor), the volume of parts going through each process step at any point in the supply chain is the same (if not higher, thanks to "global" product platform designs). Production is typically done in or near cities where large supplies of labor and supplier networks or, at least, a dependable transportation infrastructure, are available.

Once products are completed, usually in factories where hundreds or thousands of people gather to make thousands or millions of parts, they are shipped great distances, often across oceans, to the customers who want them. In the automotive industry, the most significant manufacturing sector in the United States, the average U.S.-built car is finished 90 days before it is purchased—considerably longer than it takes to make it. A manufactured product has no more value than its untransformed materials and components unless it is purchased by a customer who actually wants it in that form. Products made, but not sold, represent an inventory risk.

Because the cost of distribution often exceeds the cost of production, a better definition of manufacturing might be the creation of value through the transformation of materials from one form to another and *the delivery of that more valuable product to a buyer*. In fact, as Wal-Mart, Dell, and FedEx have all demonstrated in different ways, reducing inventory as a percentage of sales, even by just a few points, can greatly increase profits.

The Challenges Ahead

Creating economic value through manufacturing is far more important than the public and government generally acknowledge, and the more broadly manufacturing is defined, the more this becomes apparent. The world economy is based on three principal activities:

- *Agriculture* is the natural (but increasingly engineered and therefore less natural) transformation of biomaterials from one form to another form more valuable to humans. Advances in biomimetic materials and processes and the promise of biomanufacturing are gradually blurring the line between agriculture and manufacturing.

- *Construction* can be thought of as manufacturing of very large, immobile "products."
- *Manufacturing* of products, as conventionally defined, comprises the bulk of international trade.

Perhaps agriculture and construction can provide lessons for the development of constructive public policy related to U.S. manufacturing. As the result of major investments by the federal government to provide a national transportation infrastructure, the United States has the best road system in the world, which has contributed greatly to U.S. economic efficiency and prosperity. In agriculture, because of advanced technology and equipment and remarkable cooperation among government, universities, and the agricultural industry, 3 percent of the workforce produces more food than the country can consume. Yet, for nearly all of history (and for most of the world today), most of the workforce was engaged in the production of food. The workforces of newly industrialized countries are rapidly moving to manufacturing-related jobs in cities; for example, the population in China is migrating from the countryside to cities at the rate of 1 percent per year—a million people per month.

The reasons for the trend toward manufacturing are apparent in the derivation of the word itself—which literally means handmade. Through manufacturing, both "touch" labor and intellectual labor become transportable through space and time (much more easily than in construction or agriculture) and can be sold in markets that value that labor. Ironically, although the laborer himself may not be permitted to enter those marketplaces, the products in which his or her labor has been invested are welcome there. In recent decades, even though transportation technology has not changed dramatically, the *logistics* of transporting goods and keeping track of them via computers has improved dramatically, consequently lowering the cost and accelerating the movement of products from production sites to markets. With wage differentials between countries of 10 or 20 to 1—a much greater price disparity than for any commodity—products with significant labor content can bear the cost and inconvenience of being transported across borders.

Most important, trade agreements in the past 40 years have reduced tariffs and quotas and opened markets in industrialized countries to previously nonindustrial, low-labor-rate countries, such as China, India, Indonesia, Brazil, Russia, Bangladesh, and Mexico, which together account for some 3.1 billion people, more than half the world population. Products made by workers in those countries, who earn 10 percent (or less) of what workers with the same skills in G7 countries earn, appear side by side on shelves and in showrooms with domestically produced products for purchase by the mere 700 million G7 consumers who currently have most of the world's purchasing power.

More than half the value of a vehicle sold in the United States today is produced elsewhere.

Not surprisingly, the shift to global manufacturing (and what many believe is a lack of concern for the health of the U.S. manufacturing sector) has led to the loss of 2.5 million manufacturing jobs in this country since 2000. One-third of all manufactured products sold in the United States today are imported; the country exports only half that much, which has led to a huge, persistent, and growing trade deficit that for years represented 5 percent of GDP but has recently grown to 6 to 7 percent. This deficit is almost entirely attributable to the trade imbalance in manufactured goods.

In the economically important automotive industry, one-third of all vehicles bought in the United States are imported. In addition, the foreign content in "U.S.-made" cars has increased to about 40 percent. As a result, more than half of the value of vehicles sold in the United States—the largest auto market in the world—is produced elsewhere. At the same time, U.S. auto exports are meager.

Among suppliers of manufacturing technology and equipment, things are even worse. U.S. production of machine tools has fallen by two-thirds since 1998, and two-thirds of the machine tools sold in the United States are imported. In this case, the cause is not low labor rates but a lack of U.S. commitment to investments in manufacturing technology. The U.S. produces about 6 percent of the world's machine tools, about $2.2 billion worth. Japan, which has half the population, produces more than three times as much ($7 billion), and the EU, with a population not much bigger than that of the United States, produces more than six times as much ($15 billion).

As a result of this gap, the United States is no longer the recognized leader in manufacturing innovation, and, compared to its major competitors (particularly Germany), the U.S. government has invested very few taxpayer dollars in improving U.S. manufacturing technology and infrastructure, despite the fact that manufacturing was the largest sector of the U.S. economy until last year, when it was displaced by health care. Clearly, the investment gap must be addressed.

FIGURE 1 Molds for an engine set that can be produced in 36 hours with a build-box the size of a trunk. Source: Extrude Hone/ProMetal, 2003.

The challenges facing U.S. manufacturing were not unexpected. In 1998, the National Research Council Board on Manufacturing and Engineering Design published *Visionary Manufacturing Challenges for 2020*, a study sponsored by the National Science Foundation. The objective of the study was "to identify challenges and enabling technologies for manufacturers to remain productive and profitable in 2020." The report defined manufacturing in broad terms as "the processes and entities required to create, develop, support, and *deliver* products" and identified six "Grand Challenges":

- *Concurrent* manufacturing, which entails drastically shortening the time between product conception and realization.
- *Integration* of human and technical resources, which requires quick reactions throughout the "extended enterprise" workforce to serve customers with high expectations and many choices.
- *Conversion* of information to knowledge, which means (1) instantaneously transforming captured data into useful knowledge and (2) providing access to knowledge when and where it is needed.
- *Environmental* compatibility, that is, using methods that are environmentally benign, using recycled materials as feedstock, and eliminating wasted energy, materials, and human resources.
- *Reconfigurable* enterprises, which require that intra-organizational and inter-organizational structures be flexible and adaptable.
- *Innovative* processes that decrease production scale to an economical lot quantity of one; decrease dimensional scale to the manipulation of microparticles, or even nanoparticles; and fabricate and use new materials (e.g., functionally gradient materials with different properties in different areas of a single component).

One innovative area of process technology that addresses nearly all of these challenges includes features evolving from "rapid prototyping," "free-form fabrication," "layered manufacturing," "3D printing," and "Innofacturing™." Thanks partly to government support, the United States currently has a significant market and technological advantage in these technologies, all of which directly convert computer design files that describe objects as "3D models" into physical objects constructed layer by layer (i.e., assembling particles of work-piece material digitally on each layer and then adding to the work piece one layer at a time).

The most apparent advantage of these processes is the remarkable product design freedom enabled by layered construction. More important, however, is that parts can be produced, without tooling or programming, in a single, highly flexible production cell, thus eliminating the need for, or even the advantage of, scale, including volume scale. This enables *distributed* digital production, which changes just about everything about manufacturing as we now know it.

Digital Production

Phil Dickens, a professor at Loughborough University in the United Kingdom and an enthusiastic supporter of distributed digital technology, predicts that, "The impact of rapid manufacturing will be so profound, changing the way products are designed, manufactured, and distributed, that it can be described as the next industrial revolution." Unlike the first industrial revolution, which led to a migration to population-dense cities (a trend that continues in emerging industrial economies), this revolution will enable people to live where they like and produce what they need locally. Distributed digital production is the antithesis of the production line (e.g., "a factory in the home" or at least "in the neighborhood") where people will "pay for the plans, not the product," as described by John Canny, a professor at the University of California at Berkeley.

Digital production (or rapid manufacturing) transforms engineering design files directly into *functional* objects—ideally, *fully functional* objects. This technology emerged from rapid prototyping systems that first produced nonfunctional, "appearance models" (limited-use, engineering-design and marketing aids made from nondurable plastic materials). Over time, the plastic materials were strengthened until the models became fairly functional. However, the real-world benchmark materials for full functionality in manufacturing are metals.

Currently, most of the companies in the world that produce systems capable of free-form fabrication of metal components are in the United States. The ProMetal Division of my company (Ex One), for example, produces systems specifically dedicated to making metal components.

At the large end of the spectrum, metal parts can be made by using these processes to produce nonmetal casting molds. The same sand and binder that were used for years in conventional pattern-based sand casting can be 3D printed to provide precise, complex-geometry sand casting molds and cores without patterns; thus, one-off design metal castings for automotive engines can be produced in two days instead of two months (Figure 1). A 1.5 x 1 meter layer can be produced every minute. With 0.2-mm layers, roughly one liter of sand can be processed every three minutes, printed or not; typically, about a liter of printed sand molds and cores can be produced every 10 or 15 minutes.

At the other end of the spectrum, machines with a build-box the size of a matchbox can produce half a dozen gold dental copings (the part of a dental crown that fits precisely on the tooth) every hour. Thus, a dental laboratory can produce a more precise, less expensive dental restoration in one or two days, instead of a week (Figure 2).

Military spare parts can now be made when and where they are needed, as can custom-designed architectural hardware, gold jewelry, customized trophies, and parts for vintage cars. This tool-less process can even be used to make tools. Forging dies for short-run spare parts can often be made faster and cheaper than finding dies that already exist.

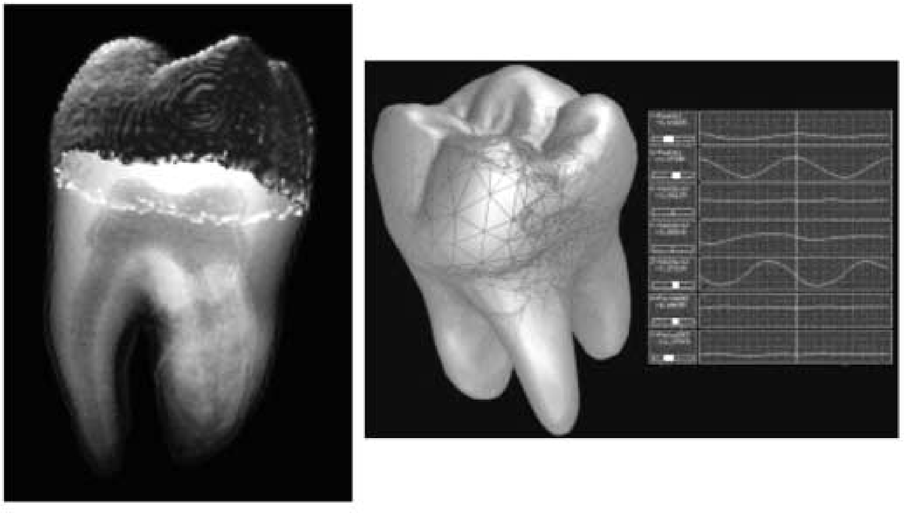

FIGURE 2 Six gold dental copings like the one shown can be produced in an hour with a build-box the size of a matchbox. Source: Extrude Hone/ProMetal, 2003.

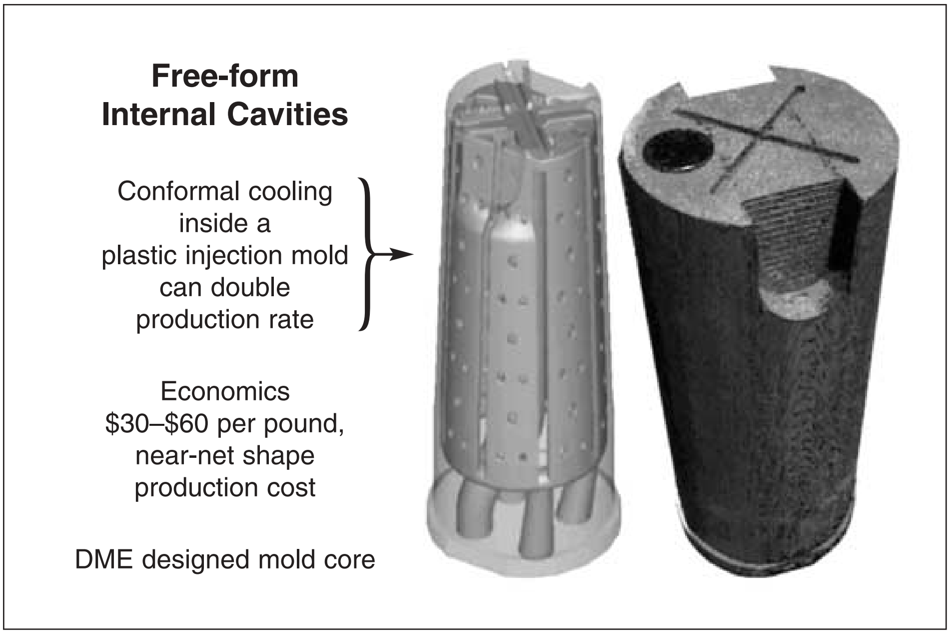

FIGURE 3 Plastic injection molds with conformal cooling passages. Source: Extrude Hone/ProMetal, 2003.

Plastic Injection Molds

For plastic injection molds, the advantages are dramatic. The conventional process of plastic injection molding entails injecting a thermoplastic polymer into a mold at a temperature high enough for the material to be "plastic," that is, capable of flowing. The material must then cool down until it solidifies in place and can be removed and handled without losing its shape. The solidification is neither instantaneous nor uniform, and the "freeze sequence" can affect dimensional precision in critical features of the molded part.

With layered production, digitally produced free-form fabricated products with complex internal geometries can be produced (Figure 3). For plastic injection molds, this means conformal cooling passages that can control and accelerate the freeze cycle of molded parts just beneath the surface of the mold cavities, enabling higher precision and higher production using the same plastic molding machines, floor space, and workforce that previously spent the bulk of the production cycle waiting for molded parts to cool down enough to stop being "plastic" and solidify. These internal geometries can be quite sophisticated and can incorporate advanced cooling features like those used to cool aircraft turbine engine blades.

Using some layered processes, components with functionally gradient materials can be produced. In the 3D printing process, the particles on each layer representing a cross section of the part are assembled by precisely "jetting" droplets of "binder" or glue. Once printing is complete, the unwanted loose particles can be separated from the "glued-together" metal powder part. The droplet-printing device can selectively print different "colors" of droplets (i.e., droplets that contain different types or concentrations of alloying agents) on different areas of the work piece; thus, different materials can be precisely placed at specific locations (Figure 4).

The metal particles in the printed, or glued-together, part are thermally fused in the sintering operation that follows (Figure 5). The alloying agent deposited at the selected sites diffuses into the particle material, altering

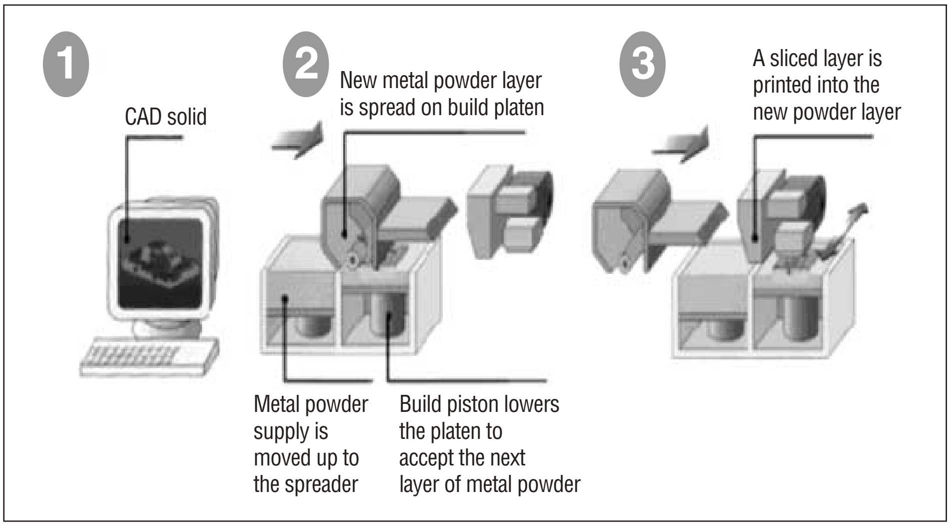

FIGURE 4 3D printing layered production process invented at MIT. Source: Extrude Hone/ProMetal, 2003.

its local physical characteristics. Unlike coating or plating, in which there can be abrupt interfacial strain from loading or temperature, a component with functionally gradient material can be made to gradually transition from, say, a hard but brittle steel surface to a tough, ductile interior without risk of delamination. This can be done by simply varying the concentrations of carbon in the binder droplets selectively printed in the part.

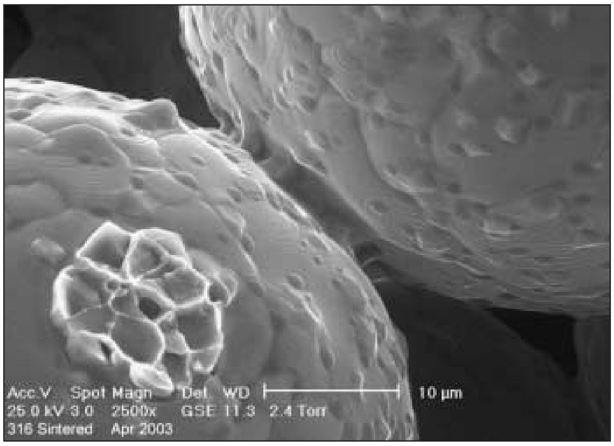

FIGURE 5 Electron micrograph showing a thermal bond produced through sintering to ensure predictable strength and dimensions. Source: Extrude Hone/ProMetal, 2003.

Conclusion

Distributed digital production, a category of processes evolving from rapid prototyping, rapid manufacturing, free-form fabrication, and layered manufacturing, is a harbinger of twenty-first-century production, which is dramatically different from the kind of "manufacturing" we know today. The fundamental nature of distributed-digital processes—the construction of functional metal work pieces by assembling elemental particles, layer by layer, with no instructions other than the computer design files widely used to define objects geometrically—is based on different assumptions than those that drove manufacturing and distribution strategies throughout the twentieth century.

The United States has an early lead in these emerging technologies, partly as a result of creative work at some of the nation's best universities (e.g., MIT, University of Texas, Carnegie Mellon University, Stanford University, University of Southern California, University of Michigan, and Johns Hopkins University) and Sandia and Los Alamos National Laboratories. The U.S. lead is also the result of the visionary spirit of technology-focused entrepreneurs who head and back companies that are pioneering these new technologies. However, the biggest factor has been the impetus provided by the U.S. government, principally the U.S. Department of Defense, which has much to gain from the development of processes for building spare parts and new products flexibly and without cost sensitivity to production volumes. Whether or not the United States maintains and strengthens its leadership position and realizes the benefits of these processes may depend on the outcome of the current debate on the role of government in providing a national "manufacturing technology infrastructure."

As the costs and wait times of tooling, programming, and "designing for manufacturing" are reduced and then eliminated, the perceived advantages of high-production volumes, concentrated manufacturing sites, and complex distribution logistics will yield to the advantages of distributed digital production—products designed to meet the specific preferences of individual customers that can be produced on or near the point of consumption at the time of consumption (e.g., automotive spare parts produced at a dealership).

The design freedom enabled by constructing objects in thin layers from particles with dimensions in microns will significantly reduce a product's component-parts count. This, in turn, will reduce product weight by eliminating attachment features and fasteners and optimize functionality by eliminating excess material and wasted energy. The particles that are not needed for the part produced can be recycled to become the next—maybe very different—part. The metal in older, no longer useful products can be locally recycled to become metal powder feedstock for tomorrow's production. Thus, inventory carrying costs and risks and transportation costs can be dramatically reduced, increasing savings in energy, materials, and labor.

Finally, because these processes are highly automated, the size of the workforce required to produce and deliver manufactured products to the customer will be greatly reduced. Consequently, low-cost, so-called touch labor will lose its competitive advantage in the production of physical objects.

The demand for innovative product designs will expand dramatically. And, because ideas will be delivered electronically, designers can be located anywhere. As design for manufacturing becomes less important, and because design superiority will be gained principally through understanding and responding to customers' tastes, designers might want to be located near their customers.

Even if products are designed remotely, however, production will be done locally. Physical objects will be produced "at home" or "in the neighborhood" from locally recycled materials. Thus, cities will lose their economic advantage, and urban populations will be dispersed.

Although the revolution promised by these technologies could have great benefits for consumers in developing countries, the economic advantages of manufacturing in areas with comparatively cheap labor will be ultimately unsustainable, and workers in poor countries are likely to suffer. Consequently, our energy and creativity must also be focused on finding other paths to economic parity in the value of equivalent human labor to hundreds of millions of low-wage workers throughout the world.

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