Metamorphic Manufacturing, or Robotic Blacksmithing –
A Vision for a New Technology

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The Third Wave of Digital Manufacturing
Agile and reconfigurable manufacturing has been dominated by two waves of innovation. The first was numerically controlled subtractive manufacturing, commonly known as CNC machining. The second was numerically controlled additive manufacturing, often called 3-D printing. There is rightly much excitement about these technologies as they have revolutionized how we make things, however, they both have shortcomings.

Machining is a time-consuming process, adding considerable cost to components because only a fraction of the original material is used in the part (the rest is turned to chips) and an expensive machine is tied up for some time to make the part.

Additive manufacturing is in its infancy, but often components are created from powders. This also produces significant waste; secondary operations are usually needed for high performance and the costs of raw materials and equipment usage can be high.

Imagine if a machine can act like a blacksmith does, squeezing and bending metal into shape, and doing this at temperatures and with deformation that actually improve the materials properties. We refer to this as metamorphic manufacturing and believe it will take its place alongside existing digital manufacturing: additive and subtractive manufacturing.
Benefits of Metamorphic Manufacturing

Blacksmiths have demonstrated that with skill and ingenuity a huge range of components (armor, swords, art) can be produced, and they can develop remarkable properties in the process, such as samurai blades with very hard sharp edges and tough interiors. However, human blacksmiths cannot be relied upon to make parts with high dimensional precision or highly reproducible properties, but with advances in machines (servo-controlled presses, precision robotics, precision optical non-contact metrology) it is possible to mimic the attributes of a blacksmith, but with dramatically improved dimensional control, reproducibility and monitoring of the process path to assure quality, allowing high performance components to be used in safety-critical applications. There can be immense cost and time savings replacing closed-die forgings with robotically blacksmithed parts, particularly if they are assured to have high properties and performance.

An example of a plastic shaping process

The first LIFT prize challenged students to develop systems that could create shapes from computer controlled deformation systems that they created (see: roboticblacksmithing.com). Oil-based clay (plasticine) was used as the workpiece material because it is relatively easy to deform and has been used for decades to represent hot metal in physical models. The winning team (Team Honey Badger, from The Ohio State University) developed a system that created both a simple bracket and horse-shoe with a single reprogrammable system that adds rotatable squeezers to a CNC machining mill. This can be adapted to metals with high force actuators.

Frame grabs from a video of the Honey Badger system (video at https://www.youtube.com/watch?v=QfIVRXLwsAw). From left to right showing basic shaping of the billet using multiple inward motions of the pincers, • Downward motion of separated platens to create the septum, • Incremental piercing using an auto-changed tool to create the central hole, • Comparing the numerically shaped plasticine to the target shape. The same system has been reprogrammed to create a horseshoe shape from the same size and shape plasticine block.
The Path Ahead
The full vision of metamorphic manufacturing integrates shaping, working and heat treatment to optimize properties and shape and local properties and recording of shape and temperature to allow assured reproduction of critical process elements. This leverages recent technical developments, but requires significant integration and advanced control systems.

There are many machines that can be used including hammers, displacement controlled presses, rollers, etc. Because deformation is provided in small increments, only modest forces are needed. Optical monitoring and Control systems are required to measure the current shape of the component and temperature field and strains can be estimated by computation. Correction routines can adjust shape the way a blacksmith would. Significant integration and an advanced closed-loop control system will be required to create advanced parts using this type of incremental deformation.

In order for this approach to truly thrive, it will need to be adopted to where validation and verification protocols exist so that components made in this way can be certified for safety-critical use, for example in aircraft. The rewards that can drive this are large. This approach promises high-quality, rapidly produced parts that have low environmental footprint, can have low-cost and are produced locally.