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Weld bead modeling and process optimization in Hybrid Layered Manufacturing

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ABSTRACT

Hybrid Layered Manufacturing is a *Rapid Manufacturing* process in which the metallic object is built in layers using weld deposition. Each layer built through overlapping beads is face milled to remove the scales and scallops and ensure Z-accuracy. The formations of single beads and overlapping multiple beads are modeled in this paper. While the individual bead's geometry is influenced by the size of the filler wire and the speeds of the wire and torch, the step over increment between the consecutive beads additionally comes into the picture for the multiple bead deposition. These models were validated experimentally. They are useful not only to predict the bead's shape but also to optimize the three process parameters.

1. Hybrid Layered Manufacturing

Hybrid Layered Manufacturing (HLM) is a *Rapid Manufacturing (RM)* process that builds metallic objects through a combination of additive and subtractive processes [1–6]. HLM uses *Gas Metal Arc Welding (GMAW)* for layered deposition. This additive process focuses on material integrity and the result is a near-net shape with sufficient machining allowance. The inherently fast CNC machining, and the subtractive process that follows, realizes the desired geometric quality. As the focuses in both these steps are different, they are individually very fast. One may subject the near-net shape to stress-relieving or heat treatment as required before finish-machining. A 3-axis HLM machine which is an integration of a 3-axis CNC machining centre with two Fronius weld-deposition units (TPS 40,000 and TPS 2700 CMT) is shown in Fig. 1. When monolithic objects are to be built, one may use filler wires of the same material but of different diameters, the thicker wire for filling the interior of the layer and the thinner one for its boundary contours. The same set up can be used for building composite objects by using wires of different materials.

The energy sources for weld deposition may be a laser, an electron beam or an electric arc. The laser has been the most popular due to its 'precision'. However, it has very poor energy efficiency in this application (2%–5%) [7]. *Laser Engineered Net-Shaping (LENS)*, *Laser-Augmented Manufacturing (LAM)* and *Direct Metal Deposition (DMD)* are some of the popular laser-based RM processes [8–11]. Of late, the electron beam is becoming popular for these applications due to its better energy efficiency (15%–20%) but it requires a high vacuum for the working environment [12]. Although electron beam welding has been popular for precise joining mostly without filler, it has not become popular for layered deposition. *Electron Beam Melting (EBM)* of Arcam (Sweden) is a popular RM process using an electron beam but it is a *powder-bed* technology and not the *deposition* type. However, it may be just a matter of time before more electron beam based deposition processes too emerge due to their attraction of the higher energy efficiency over lasers [13].

Fig. 2 shows some metallic objects realized using different RM processes. As is obvious from these figures, all of them produce only near-net shapes and rough surfaces. These cannot be used in many applications unless they undergo post-machining. Therefore, there are no major differences among laser, electron beam and arc welding in terms of the finish and material integrity. Arc welding has the added advantages of higher deposition rates, lower costs and safer operations. The deposition rate of laser or electron beam is of the order of 2–10 g/min, whereas 50–130 g/min have been reported in arc-deposition and it can reach as much as 800 g/min with proper heat management [2]. Thus,laser or electron beam may be overkill for the tooling and component applications barring a few exceptions such as the realization of miniature objects.

Fig. 3(a) shows the CAD models of an *egg template* of a refrigerator and its injection molds. The near-net shapes of these monolithic injection molds were made by alternately weld-depositing a layer and face milling. Each layer was 2.0 mm thick which is an order of magnitude larger than the existing RP

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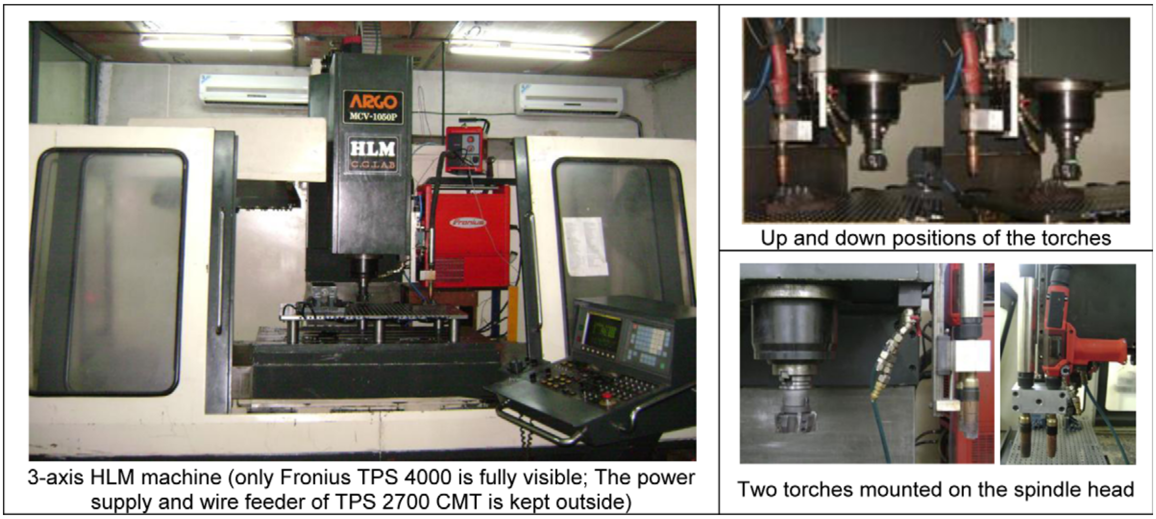
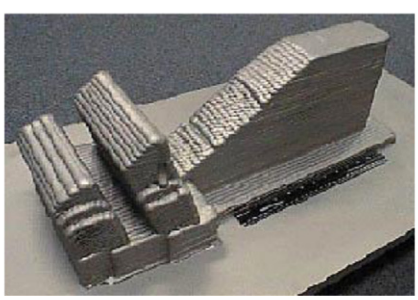


Fig. 1. The 3-axis Hybrid Layered Manufacturing machine at IIT Bombay.

(a) LENS (OptoMec).

(b) DLF (FhG, Dresden).

(c) Arcam.



(d) LAM (AeroMet).

(e) HLM (IIT Bombay).

Fig. 2. Comparison of surface quality of RM processes using laser, EB and arc sources.

processes. These molds had already been manufactured through the subtractive route by the company and their cost and time were available for comparison. The HLM approach for this case-study of an *egg-template* was cheaper by 22.3% and faster by 37.5% over the traditional CNC approach [14]. These savings arise from (a) elimination of a roughing operation (savings of machine hours and programming time) and material saving. HLM's unique capability is the *economic manufacture* of *composite injection molds* with *conformal cooling ducts* in *discrete adaptive layers*. Note that these cooling ducts have a triangular cross-section so as to build them without a support structure in this deposition process. The top of Fig. 4 shows the CAD model of the punch of an injection mold. Its case of 10 mm thickness shown in yellow color is made of P20 tool steel. Its core (depicted in green color) consisting of a conformal cooling duct is built using mild steel. The building process used discrete adaptive thicknesses, i.e., while the yellow and green zones are built in layers of 2 mm, the pink zone around the triangular cooling duct is built in layers of 0.5 mm. HLM also has promising applications in component manufacture by adopting a combination of strategies including 5-axis kinematics. The various stages of manufacturing an Al–Mg5 propeller of a MAV using the 3-axis HLM is illustrated in Fig. 5. In summary, the benefits of HLM increase with the increase in *geometric complexity*, *sparseness* and *material cost*.

Understanding the weld-bead formation and the interference between overlapping beads is essential for optimizing the process parameters. This problem is defined in the next section along with a literature review. The single and multi-bead models are presented in Sections 3 and 5 and the same is experimentally validated too.