Circular Manufacturing Roadmap: Hybrid Processes for Rapid Response and Resource Efficiency

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Introduction

Circular manufacturing is becoming a key paradigm for creating sustainable, resilient, and resource-efficient manufacturing systems. Contrary to the traditional linear manufacturing model of single life-cycle usage, circular manufacturing aims to keep materials, components, and products in use for as long as possible through reuse, repair, remanufacturing, and recycling. To realize the full potential of circular manufacturing, production systems must adapt quickly to changing conditions, use materials more responsibly (including recycled materials), and respond effectively to disruptions in supply and demand. Flexible and hybrid processes are becoming central to achieving these goals, as they combine adaptability, precision, and efficient resource use to support circular practices.

This notion of a hybrid approach providing better advantages than the individual processes is also true in the case of Manufacturing and its three broad approaches, viz., additive, subtractive, and formative. Material is added, removed, and deformed in each of these processes. While each of them individually have a lot of advantages, they also suffer from certain limitations. To make the most efficient use of the material and energy involved, each of them must be harmonized with other manufacturing processes. The purpose of these hybrid processes is to enhance their advantages whilst at the same time reducing their disadvantages. By combining these processes, Hybrid-Manufacturing technologies can not only enlarge the geometrical configurations possible but also enhance overall process capabilities, particularly with respect to component quality and the efficient utilization of resources (materials, energy, time etc.).

Numerous hybrid manufacturing processes are possible; however, this article presents selected hybrid approaches developed by the authors' groups at IIT Hyderabad.

These efforts focus on the hybridization of additive–subtractive and additive–forming processes to demonstrate the potential of hybrid manufacturing in terms of enhanced productivity, increased geometrical complexity, and improved material properties

Additive and Subtractive

The combination of CNC machining and additive processes may provide a new substantial solution to the limitations of additive processes due owing to the high accuracy that machining processes offer. Generally, hybrid additive and subtractive manufacturing processes' methods use an additive process to build a near-net shape which will be subsequently machined to its final shape with desired accuracy by a subtractive process.

In this setup, a Gas Metal Arc Welding (GMAW) torch is mounted in proximity to a CNC (Computer Numerical Control) machine, enabling the system to perform both material deposition and machining operations within a single platform. This integration is achieved through a combination of mechanical and electrical modifications. During the integration, changes to the mechanical and electrical systems are done without the need for any proprietary information from the machine builder or the control developer.

Mechanically, the welding torch is positioned near the milling spindle so that deposition and milling can be carried out sequentially without repositioning the workpiece. The welding unit is electronically interfaced with the CNC controller, typically through existing relays such as the coolant or additional CNC relay, allowing the welding system to be switched on and off as required. Together, these mechanical and electronic integrations enable integration of additive and subtractive manufacturing within a single workstation.

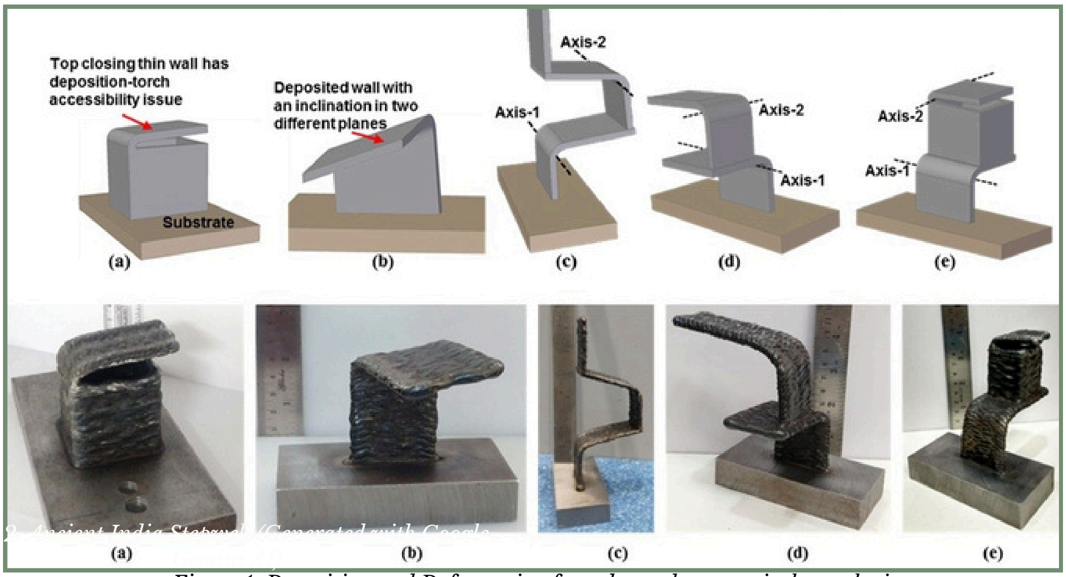

Figure 1: Deposition and Deformation for enhanced geometrical complexity

Additive followed by Deformation

Wire-Direct Energy Deposition (W-DED) techniques in Metal AM allow part-fabrication at higher deposition rates and lower costs. Due to the lack of any support mechanism, these processes face challenges in fabricating overhanging features. Inherent overhang capability of weld-beads and higher-order kinematics can help realize certain complex geometries. However, significant challenges like non-uniform slicing, constrained deposition-torch accessibility, etc., limit the efficacy of these approaches.

This facet of research at IITH, describes a Deformation aided Deposition process to overcome some of those limitations and manufacture complex metallic components. It is based on a sequential combination of deposition and bending processes: a shape fabricated through W-DED (Wire based Directed Energy Deposition) is bent to realize the required shape (in addition to shape complexity, this approach can also be used by others for material property enhancement).

The Deformation- aided- Deposition process consists mainly of two stages. The first stage is meant for deposition in the form of a GMAW welding torch and the second station corresponds to the bending which is to be carried out with a hydraulic press employing customized dies and punches. The component deposited in the first stage can move to the second station to bend the component to a required shape/geometry. After this step, the component can again move back to the deposition stage for further processing. The desired shape can be obtained through this series of activities. Figure 1 shows a few set of sample geometries fabricated using this approach.

Forming Followed by AM

The proceeding section presents work where deposition precedes deformation. This helps in enhancing the mechanical and/or geometrical complexity of AM made parts. The inverse is also possible, ie., deposition happening on a formed component. This approach is beneficial when required to fabricate complex geometries. When overhang features are involved, deposition become difficult due to gravity and torch accessibility constraints.

Hence, the current research has been focused work package attempts on hybridization of forming and deposition with focus on product complexity by exploiting the geometrical freedom possible in both processes. To this end, Double Sided Incremental Forming (DSIF) and W-DED (Wire-based Direct Energy Deposition) are used in the present work.

Figure 2 shows one of the geometries chosen to illustrate this approach. In first stage, the various features DF1 and DF2, in the geometry are extracted (DF1 and DF2 in this case). The feature DF2 can be fabricated on a three-axis AM machine, whereas the feature DF1 has a limitation in the conventional W-DED process due to lower surface inclination (lack of support structure). Hence, the deformation/form feature FF1 (which corresponds to DF1) is realized first to act as the non-planar substrate for the subsequently deposition process. Figure 2 illustrates the fabricated part, demonstrating the potential of this method to provide non-planar surfaces for deposition.

Conclusions

The objective of the present work is to demonstrate the potential benefits of hybrid manufacturing techniques as enablers of circular manufacturing. By combining additive manufacturing with complementary conventional processes, these hybrid approaches expand capabilities for repairing worn components, extending product lifetimes, and incorporating recycled or alternative materials into new or existing parts.

Furthermore, by facilitating rapid response manufacturing, improving resource efficiency, and reducing environmental impact, hybrid manufacturing methods directly support sustainability objectives and provide a practical roadmap for implementing circular manufacturing practices.

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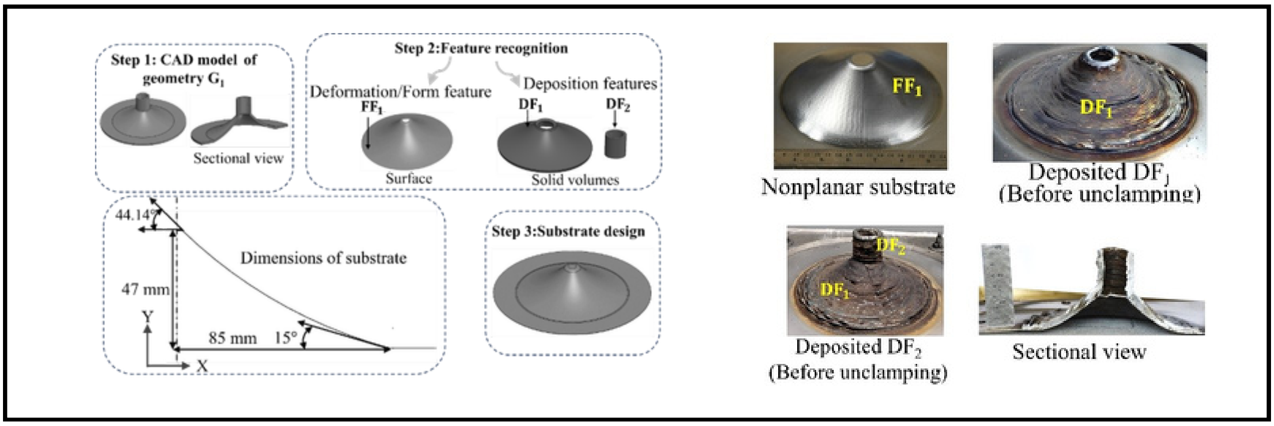

Figure 2: Steps in the substrate design for forming process (to act as starting point for AM) ; Fabrication of the component with deposition on DSIF formed substratermation for enhanced geometrical complexity