Shape Deposition Manufacturing

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Abstract

One challenge for solid freeform fabrication has been to develop the capability to directly create functional metal shapes which are dense, metallurgically bonded, geometrically accurate and with good surface appearance. Shape Deposition is a manufacturing paradigm which attempts to address these issues. It incorporates the advantages of several processes including solid freeform fabrication (complex geometries, rapidly planned), 5-axis CNC machining (accuracy, smooth surfaces), shot-peening (for stress relief) and 'microcasting' (a high-performance, weld-based material deposition process). These processes are integrated within a CAD/CAM system using robotic automation. This paper will present the current research in this effort.

Introduction

While functional metal shapes have been built with solid freeform fabrication (SFF) through postprocessing and/or conversion methods [1], it remains a goal to be able to *directly* build high performance metal shapes. Metal parts which are fully dense, metallurgically bonded, have accurate dimensions and good surface appearance are often required for such applications as fabricating custom tooling (e.g. injection molds) and functional production-ready prototypes (e.g. engine components). An early system, called MD* [2], built prototype metal shapes directly with thermal spraying. While the MD* approach incorporates a versatile material deposition process, it has several limitations which are also common to several other SFF processes. The parts exhibit a stair-step surface texture and it is difficult to achieve the accuracy, precision and resolution which can be achieved with traditional shaping methods such as CNC machining. Sprayed material also exhibits porosity, and the mechanical strength is poor compared to cast or welded materials. In addition, the buildup of residual stress through thermal gradients during layered solidification can lead to warpage and delamination [3].

Other incremental material deposition approaches which are based on welding, such as Shape Melting [4] and 3D-Welding [5], produce superior material properties, but have been limited in geometric complexity and require finishing machining operations. In our experience, no single SFF or conventional fabrication process will satisfy all the requirements for rapidly and *directly* creating high performance metal parts. To address this challenge we are investigating an approach called Shape Deposition Manufacturing (SDM) [10 - 14] which combines the benefits of SFF (i.e., quickly planned, independent of geometry), CNC milling (i.e., accuracy and precision with good surface quality), weld-based deposition (i.e., superior material properties) and shot peening (i.e., control of internal stress buildup). This paper describes the concept of Shape Deposition, a novel, weld-based deposition process called microcasting and thermal and stress related issues. Further, a testbed implementation of SDM is discussed and examples are presented.

Shape Deposition

The basic steps for building parts with Shape Deposition is depicted in Figure 1. To form each layer the growing shape is transferred to several processing stations. First, the material for each layer is deposited as a near-net shape using a novel weld-based deposition process called microcasting [7] (Fig. 1a). The part is then transferred to a shaping station, such as a 5-axes CNC milling machine, where material is removed to form the net shape (Fig. 1b). In the next step the part is transferred to a stress-relief station, such as shot-peening, to control the buildup of residual stresses (Fig. 1c). The part is then transferred back to the deposition station, where complementary shaped, sacrificial support material is also deposited. Each of these operations are described in detail below.

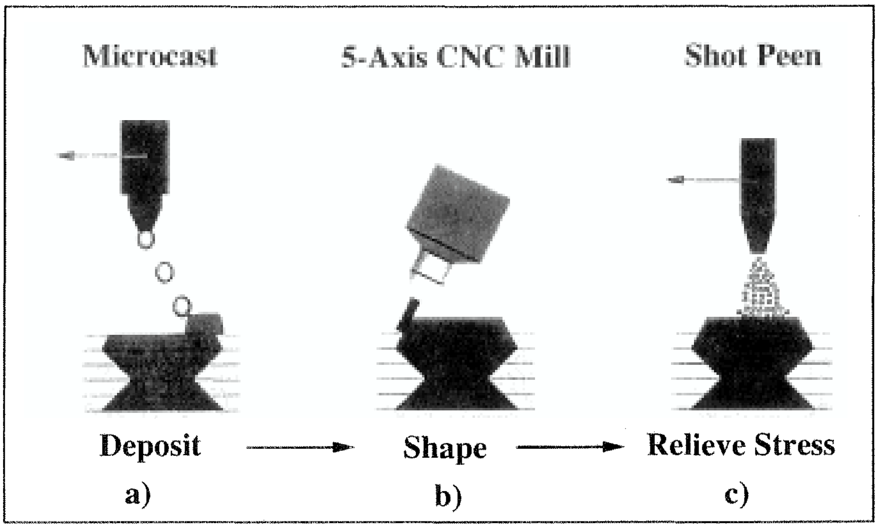

Figure 1: Creation of a layer using SDM

In contrast to SFF processes, Shape Deposition decomposes the CAD model of the part into slices which maintain the full three-dimensional geometry of the outer surface. The total layer thickness and the sequence for depositing the primary and support materials depends upon the local surface geometry. Consider the shape in Figure 2 which represents three fundamental features which can be found in a layer; non-undercut (relative to the build direction), undercut, and a combination of both.

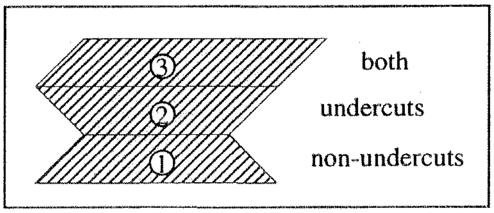

Figure 2: Cross-section of example shape

This shape can be formed as follows:

• In the first layer, which contains only non-undercut features (Fig. 3), the primary material is deposited (Fig. 3a) and shaped (Fig. 3b) first. This layer is completed by depositing the support material (Fig. 3c) and planing the to surface (Fig. 3d).

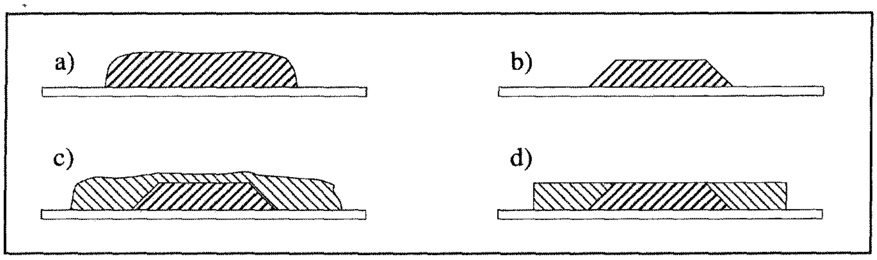

Figure 3: Manufacture of non-undercut features

• The second layer, which contains only undercut features (Fig. 4), is created by depositing (Fig. 4a) and shaping (Fig. 4b) the support material first. This forms a molding cavity into which the primary material is then deposited (Fig. 4c) and the layer is finished by planing the top surface (Fig. 4d).

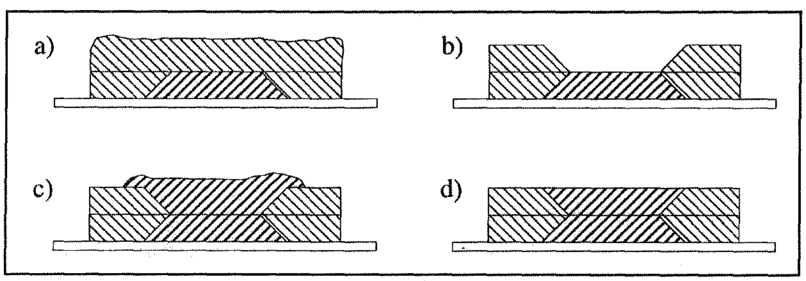

Figure 4: Manufacture of undercut features

• For the third layer the support material must be subdivided (Fig. 5). The section of the support material with no undercuts is deposited and shaped first (Fig. 5a). Next, the primary material is deposited and the non-undercut surfaces are shaped (Fig. 5b). Finally the remaining portion of the support material is deposited and the layer is planed (Fig. 5c). In general, for layers containing a combination of undercut and non-undercut surfaces, the individual materials have to be split into smaller segments. Each segment contains undercut surfaces only in those areas which are adjacent to previously deposited segments of the layer.

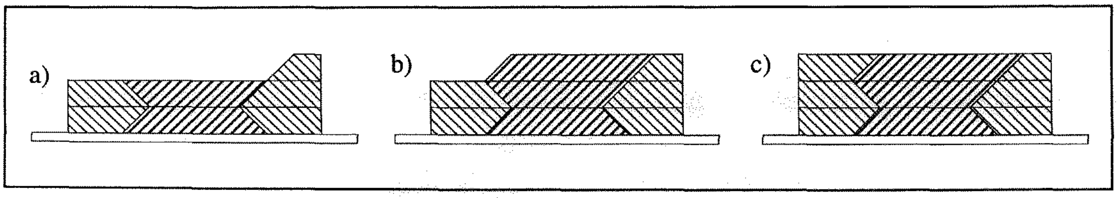

Figure 5: Manufacture of arbitrary layers

Figure 6 shows a comparison of cross-sections of the part manufactured with SFF techniques and Shape Deposition. While SFF needs a relatively large number of layers Shape Deposition can produce thicker layers and eliminates the stairstep texture of the surface.

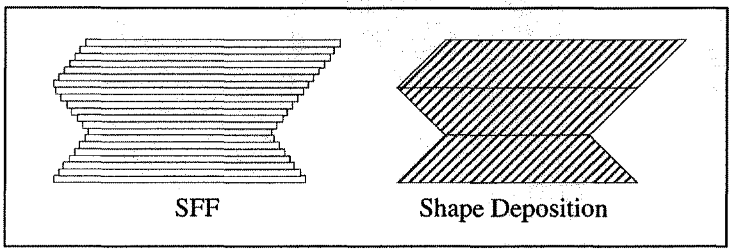

Figure 6: Comparison between SFF and Shape Deposition

Microcasting

Thermal deposition technologies have been investigated in SDM in order to produce high quality material. However, conventional deposition approaches including thermal spraying and welding have several limitations. The molten droplets created by thermal spraying are relatively small (order of magnitude 50 μm) and therefore do not contain enough heat to remelt the underlying surface. Instead, mechanical bonds are predominately formed, and adhesive and cohesive strength are relatively low. While this leads to undesirable material properties, the low heat transfer into the substrate preserves previously shaped layers. In contrast, weld-based deposition approaches, such as MIG or plasma welding, locally remelt the substrate where the feedstock material is deposited, thus forming metallurgical bonds. However, the relatively large heat transfer will affect the shape of underlying material.

A compromise between thermal spraying and welding is required to achieve metallurgical bonding without destroying underlying geometries. Microcasting is a droplet-based deposition process which addresses this challenge. In contrast to the droplets produced with thermal spraying, microcast droplets are relatively large (1 to 3 mm dia.). They contain sufficient heat to remain significantly superheated until impacting the substrate, and rapidly solidify due too significantly lower substrate temperatures. The microcasting apparatus can be implemented with conventional welding equipment configured in a non-transferred mode [11]. Microcasting creates a stream of individual droplets at a rate between 1 and 5 droplets/second. By controlling the superheat of the droplets and the substrate temperature, conditions can be attained, such that the impacting droplets superficially remelt the underlying material (on the order of 10 μm deep) [6] leading to metallurgical interlayer bonding.

Microcasting is used to deposit not only the primary material but also the material for the support structure. One suitable combination of materials is stainless steel for the main material and copper for the support structure. The copper support structure is etched away with nitric acid after the part has been completed. When the stainless steel is deposited it does not deeply penetrate the copper because of the high thermal conductivity of copper. On the other hand, the copper does not deeply penetrate the stainless steel because of its lower melting temperature [7].

Discussion of Thermal and Stress-Related Issues

Key issues in shape deposition manufacturing originate from temperature gradients caused by fusing molten droplets onto previously deposited layers. As described earlier, for the establishing of a solid bond the molten droplets need to be superheated such that they can remelt a thin surface layer immediately after impact. Heat transfer calculations to determine the conditions for remelting have shown an inverse relationship between minimum droplet temperature versus minimum substrate temperature [6]. Intuitively obvious, if the droplet temperature goes down the substrate temperature needs to be increased accordingly. However, due to the latent heat there is a threshold temperature below which the droplets will crystallize without remelting the underlying solid. Experiments have confirmed these calculations.

Temperature gradients in layered material deposition are always associated with internal stresses or distortions. Imagine bonding a hot piece of material on top of a substrate with a lower temperature. After both pieces have cooled down and converged to the same temperature the material portion which was originally hotter will have contracted more then the colder one. This puts the hotter piece in a state of tension while the colder piece will be equivalently compressed. Unless external forces such as the sacrificial support material or material layers underneath lock the joined material layers in place they will bend upwards until having reached static equilibrium. Problems like this occur in a variety of manufacturing applications ranging from welding or thermal spraying to the fabrication of VLSI chips and other Solid Free Forming processes such as Selective Laser Sintering or Shape Melting. One goal in Shape Deposition Manufacturing is to compensate for the tensile stress in the upper most layer by introducing a compressive stress. In materials which can be plastically deformed such as metals this can be accomplished through shot peening [8]. Ideally, the impacting shots create a plastic shear wave which traverses to the remelted zone eliminating the elastically stored tension energy. In practice, this is difficult to realize and in all likelihood a thin layer of compressively stressed material will overcompensate a layer of residual tension stress right above the remelted zone.

Another means of minimizing temperature gradients during molten droplet deposition is increasing the substrate temperature. However, the overall temperature of the article embedded in the sacrificial support structure needs to be kept below a certain level to prevent melting of the later. For primary/sacrificial support material combinations which have been investigated to date the support material had always a melting temperature well below that of the primary material of the target article. Planning material deposition strategies must take into account these conflicting goals of minimizing temperature gradients versus overheating and possibly melting the support structure. A quantitative understanding of temperature gradient, associated internal stress build up, and thermal energy accumulation is a prerequisite for generating quality parts in Shape Deposition Manufacturing.

Testbed Facility

In order to have the flexibility to investigate different subprocesses, robotic automation was used to implement the SDM process [9]. The testbed facility (Fig. 7) consists of four processing stations; CNC milling, thermal deposition, shot-peening and cleaning. The growing parts are built on pallets which are transferred from station-to-station using a robotic palletizing system. Each station has a pallet receiver mechanism. The part transfer robot places the pallet on the receiver which locates and clamps the pallet in place.

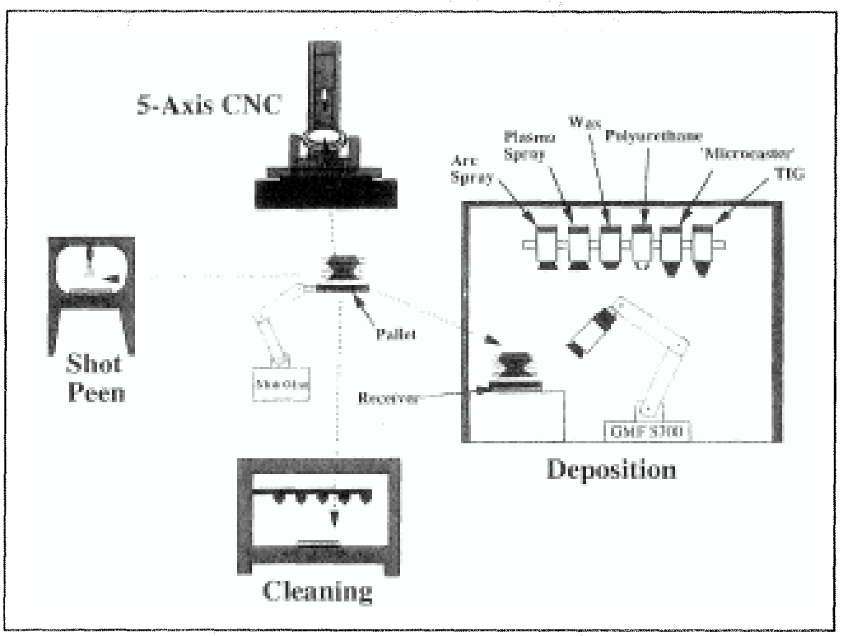

Figure 7: Shape Deposition lab configuration

The deposition station consists of an acoustic chamber (for noise abatement and dust containment), an air handling system (for dust filtration and collection) and a robotic deposition system. The deposition robot is equipped with a tool changing wrist and is able to acquire one of several different deposition torches which are mounted to a docking mechanism. The current sources include arc and plasma sprayers, as well as MIG, plasma and 'microcasting' welders. To deposit material, the robot picks up the appropriate torch and manipulates it over the growing shape.

The shaping station is a 5-axis CNC milling machine with an 21-head tool changer mechanism (i.e., it can automatically acquire one of 21 different end-mills). The hydraulically-actuated receiver used in this station is able to repeatedly locate the pallet within approximately 0.0002 inches. When cutting fluids are used in milling operations, the pallet is then transferred to a cleaning station to remove residuals. The shot peening station, which uses a conventional pressurized media delivery system, also incorporates grit-blasting capabilities for surface preparation prior to conventional spraying operations.

Examples

While the Shape Deposition process is at an early stage of development, we have built several test parts. For example, Figure 8 shows a complexly shaped artifact which was made for the IMS (Intelligent Manufacturing Systems) consortium. This is a 308 stainless steel part which was embedded in sacrificial copper support material.

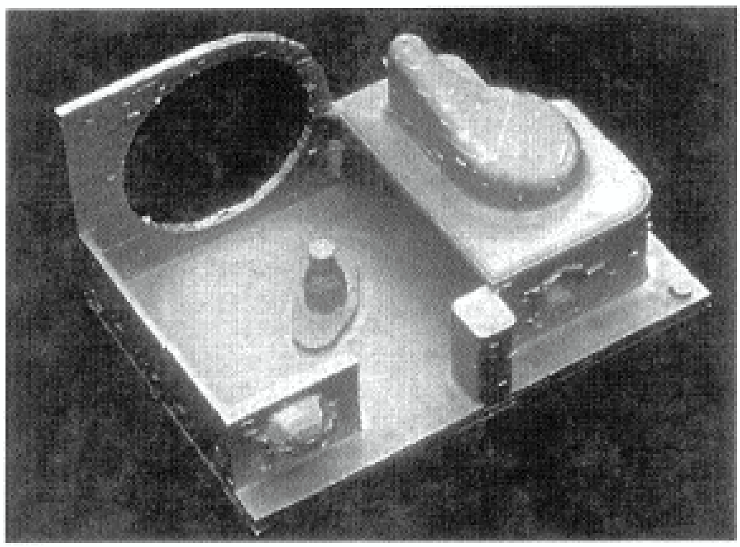

Figure 8: IMS-T2

Data from mechanical testing of this material combination on individual tensile test specimens is shown in Table 1. The tensile strength for 308 weldments is specified at 597.2 MPa (86.6 ksi), the yield point at 399.9 MPa (58.0 ksi) and the elongation at 35%. The average tensile strength of microcast 308 is thus 17% higher, the yield point is 20% higher, and the elongation is 28% higher. While layer to layer bonding strength has not been tested yet, metallographic evidence suggests metallurgical bonding between the layers.

	tensile strength [MPa] ([ksi])	0.2% offset yield [MPa] ([ksi])	elongation [%]
min.	663.2 (96.2)	406.9 (59.0)	34.1
avg.	677.2 (98.2)	481.1 (69.8)	44.8
max.	685.7 (99.5)	499.5 (72.4)	58.4

Table 1: Tensile test results for 308 stainless steel

Conclusions

The implementation of a testbed facility and the creation of several test parts have demonstrated the feasibility of Shape Deposition Manufacturing. However, several issues must be addressed to realize the creation of fully functional shapes. In the current microcasting setup there is no direct control of the temperature of the underlying substrate or of the droplet's temperature, size and trajectories. This results in several problems which can lead to the existence of voids in the deposited material and excess remelting. To reliably create high quality deposits, a closed loop control system must be developed. The issues involving residual stress buildup during deposition have to be identified, and the influence of shot-peening must be further investigated.

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