RAPID PROTOTYPING TECHNIQUES FOR HETEROGENEOUS OBJECT MODELING
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Abstract- Although, in recent years, several schemes have appeared about the computer aided modeling of simple heterogeneous objects (HO), but relatively few have focused on rapid prototyping of heterogeneous objects with simultaneous geometry intricacies as well as compound material variations. Existing schemes more or less fail to resolve pending issues pertaining to generalization and uniformity of representation schemes for rapid manufacturing of heterogeneous objects. This paper focuses on resolving such issues and addresses requirements for rapid manufacturing of HO. A modus operandi has been proposed for rapid manufacturing of HO. The process planning tasks like solid modeling, material modeling, slicing, orientation etc. are discussed in brief. The available rapid prototyping techniques are classified. The few rapid techniques capable of fabricating heterogeneous objects are identified.

Keywords: Heterogeneous Object, Rapid prototyping, Modeling, Slicing, Process Planning

I. INTRODUCTION

A. Conventional Manufacturing
In the traditional manufacturing processes, lower product cost and shorter time to market are always the goals that the industry pursues to achieve competitiveness. A traditional production process can be divided into several basic stages such as design, manufacturing and assembly. Design consists of functional design, conceptual design and detailed design. The commonly used methods for manufacturing engineering products include a number of operations i.e. casting, milling, turning, drilling etc. In an attempt to increase productivity, both academia and industry have made a lot of efforts and taken many effective measures to improve and enhance every aspect of production processes. Some of these are:
- Many optimization design theories and methodologies have been developed [18]. Design for manufacture and design for assembly are the most successful examples and are widely used in the industry.
- A variety of advanced integrated manufacturing devices such as computer numerical control machining centers and flexible manufacturing systems are employed.

Due to use of these optimization techniques and advanced manufacturing technologies, the processes and production costs have been greatly reduced in past few decades. However, costs in terms of time i.e. prototyping, testing and fabrication; special tooling and manpower constitute quite a large portion of the total cost in conventional manufacturing systems.

Rapid manufacturing processes have reduced these limitations and provided the faster methods for product design and development.

B. Rapid Manufacturing Technology
Rapid manufacturing processes can be categorized into subtractive manufacturing (High speed CNC machining) and additive manufacturing processes. Additive rapid manufacturing processes refer to the fabrication of physical parts layer by layer under computer control, which is fundamentally different from the traditional manufacturing methods.

It involves successively adding raw materials layer by layer to create a solid of some predefined shape. Rapid prototyping (RP) is a 2.5 D process, stacking up layers while conventional manufacturing is inherently a 3D process.

Rapid Prototyping has also been referred as solid free-form fabrication, computer automated manufacturing, and layered manufacturing. Rapid prototyping is widely used for rapid fabrication of physical prototypes of functional parts (important in the design stage), patterns for molds, medical prototypes (implants, bones), consumer products, etc. In some cases, the RP part can be the final part, but typically the RP material is not strong or accurate enough.

When the RP material is suitable, highly convoluted shapes (including parts nested within parts) can be produced because of the nature of RP. RP has many advantages when compared to conventional manufacturing methods, which are briefly discussed below:
- Geometric complexity has a significantly less impact on the fabrication process.
- It involves direct fabrication i.e. it does not involve tooling, fixturing and other peripheral activities of conventional manufacturing. Therefore, it is possible to manufacture physical part from CAD model directly in a much shorter time.
- Modifications can be easily incorporated into the model during any inter stage, which facilitates the optimization of design and eliminates the time-consuming and expensive alterations at a later production stage. As a result, product development costs and lead time are substantially reduced. Thus, RP considerably reduces new product development costs and the time to reach market.

The principle of RP process is illustrated in Fig. 1 [1].
The basic methodology for all current rapid prototyping techniques is summarized as follows:

- The geometric CAD model of the product to be fabricated is constructed and converted to Stereolithography (.STL) file format for information processing to RP set up.
- The RP machine processes the .STL file by creating sliced layers of the model and transmitting the motion control signals to RP machine for physical processing of part.
- The first layer of the physical model is created. The model is then lowered by the thickness of the next layer, and the process is repeated until completion of the physical model.
- The model along with supports, if any, is removed. The surface of the model is then post-processed i.e. cleaned and finished.

II. AVAILABLE RP TECHNIQUES

Since 1990, extensive research and development work has been carried out in the field of rapid prototyping and in particular, works on laser sintering and deposition. Commercial implementations of the rapid prototyping became available in the late 1980s with the Stereolithography machine by 3D systems, USA. Since then, this industry has flourished and current RP systems can be easily classified in the following three categories:

a) Liquid Based
b) Solid Based
c) Powder Based

Liquid based RP systems have the initial form of its material in liquid state. Through a process; commonly known as curing, the liquid is converted into solid state. The following RP systems fall in this category:

i. Stereolithography Apparatus (SLA)
ii. Solid Ground Curing (SGC)
iii. Solid Object Ultraviolet Laser Printer (SOUP)
iv. Rapid Freeze
v. Micro-fabrication

Except for powder, solid based RP systems are meant to encompass all forms of material in the solid state. In this context, the solid form can include the shape in the form of a wire, a roll, laminates and pellets. The following RP systems fall in this definition:

i. Laminated Object Manufacturing (LOM)
ii. Fused Deposition Modeling (FDM)
iii. Paper Lamination Technology (PLT)
iv. Multi-Jet Modeling (MJM)
v. Melted Extrusion Modeling (MEM)

The above technologies either use cutting and gluing/joining method or melting and solidifying/fusing method.

Powder by-and-large is in solid state. However, it is intentionally created as a category outside the solid systems. Some of the RP technologies that fall in this class are:

i. Selective Laser Sintering (SLS)
ii. Three-Dimensional Printing (3DP)
iii. Laser Engineered Net Shaping (LENS)
iv. Multiphase Jet Solidification (MJS)
v. Direct Metal Deposition (MDM)
vi. Laser-Based Flexible Fabrication (LBFF)

All the above processes employ the joining(binding) method. The method of joining(binding) differs amongst the above systems as some employ a laser while others use a binder/glue to achieve the joining effect.

Since the first commercial RP process, Stereolithography apparatus (SLA) was invented in 1988, many RP processes have gained popularity e.g. Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Three-Dimensional Printing (3DP), etc. As the use of RP technologies can result in a significant reduction in the prototyping time, current RP technologies are referred as rapid prototyping technologies.

For different RP processes, different materials (polymer, ceramic, wax, paper, etc.) and material combining methods (sintering, binding, adhering, solidifying, etc.) are employed. However, the basic principles of these RP processes are either the same or almost similar.

III. HETEROGENEOUS OBJECT MODELING FOR RAPID MANUFACTURING

As discussed earlier, researchers have been focusing on the vast applications of HO. These functional part scan be realized through rapid manufacturing processes. Conventionally, no material information was considered during modeling, analysis and rapid manufacturing. However, the heterogeneous objects cannot be dealt with the same strategy and requires a more advanced model, which should have varying material composition information along with part geometric information. Thus, developing a computer-aided model for rapid manufacturing of HO is one of the challenging research topics, particularly for graded material objects. The HO model should be intuitive in representing geometry, topology and material information simultaneously; capable of representing complex solids; compact, exact and compatible [2-5]. This is essential to exchange data among design, analysis and manufacturing process plan domains.

IV. PROCEDURE FOR RAPID MANUFACTURING OF HETEROGENEOUS OBJECTS
The procedure for rapid manufacturing of heterogeneous objects is described in Fig. 2. Heterogeneous object design is a close loop process which involves three steps: determine the configuration of the object, design the material variations as per functional requirement and analyze the object for certain constraints and loading conditions. The geometry of the object is modeled, and materials are distributed in the object domain as per functional requirement. At this stage the user is still uncertain on whether the designed objects can really meet the functional requirements in terms of prescribed properties. Such function analysis could be properly conducted with available numerical approaches especially finite element analysis (FEA) methods. Generally, the CAD models assume that all the necessary geometric, topological and material information could be easily retrieved at FEA platform and the designed HO could be properly evaluated via FEA. Such an assumption for CAD modeling and FEA of HO creates a gap and makes it tedious for both designers and engineers to exchange the necessary information in the entire design process. Thus, the computer aided model should be capable of transferring material information along with geometric one for FEA of HO so that the best configuration can be found out. Once the object design is optimized, 3D CAD model of HO is modeled using final designed specifications i.e. both geometric and material. The computer aided model of HO is then transferred to rapid manufacturing set up. The necessary preparation tasks i.e. orientation, support generation, slicing, etc. to start rapid manufacturing of HO are termed as process planning tasks. During rapid manufacturing, computer aided 3D model of HO is sliced into many thin 2.5D layers having uniform/variable layer thickness and material distribution. The distribution of materials in each layer is determined using scan algorithms. Each layer is tessellated into small regions to establish the composition of materials at each point. Based on material composition information, multiple materials are spread over each region. Finally all layers are joined together by different methods to form the HO.

To produce high-performance functional components, such as molds and dies that are free of the defects mentioned above, a novel LC-based RP technique, namely, laser-based flexible fabrication (LBFF), has been developed. This technique is different from others in the following aspects: (1) use of materials to make parts with functionally graded composition and microstructure; (2) application of shaped laser beams to produce desired surface finish and dimensional tolerance.

V. RP PROCESSES CAPABLE OF MANUFACTURING HO

Rapid Prototyping (RP) processes have the potential to fabricate heterogeneous objects. These processes require an efficient and effective computer aided model that can provide necessary information at each step during fabrication. The material can be varied continuously to yield a heterogeneous object with varying material properties at the selected locations in the object domain. The deposition of correct material can be explicitly controlled through computer aided model thereby providing unique opportunities to selectively deposit material. This leads to the direct fabrication of multi-material structures. Besides, embedding of prefabricated electronics or other components is also possible (e.g. an outer shell of tool steel with interior copper cooling channels). Furthermore, different materials, in varying proportions, can be deposited on a single layer and the part can be endowed with microstructure.

Fig. 2 Procedure for fabrication of heterogeneous objects

Thus, computer aided model plays an important role in the object design and rapid manufacturing of heterogeneous objects [21]. The computer aided model should be able to convey the geometry as well material information at each point within the object and should reveal the information at each stage during design and rapid manufacturing of heterogeneous object.
and to reduce residual stresses and dilution in the functional layers; and (3) use of a quasi-coaxial nozzle for powder delivery. Since LBFF involves direct interactions between moving heat source and powder materials, the phenomena of mass transport, heat transfer, and fluid flow makes it rather complex.

Wu [25] has proposed another RP process i.e. 3D Printing which is particularly well-suited for the fabrication of parts with local composition control (LCC). 3D Printing creates parts in layers by spreading powder, and then ink-jet binding materials into the powder-bed. Merz [16] has introduced Shape deposition manufacturing (SDM) which integrates material deposition and material removal processes. Another type of RP process - ballistic particle manufacturing (BPM) builds prototypes by solidification of molten material. Besides the BPM process, a similar RP process - fused deposition modeling (FDM) can be employed to build multiple material objects.

Developing a RP system for manufacturing of HO is beyond the scope of current work, however, the exposure to RP processes capable of manufacturing HO provides the basic knowledge of process requirements as this would help in developing a proper support system for of heterogeneous objects for additive manufacturing.

An essential task in rapid manufacturing is to plan the fabrication process. It is commonly referred as process planning and includes orientation determination, support structure identification, slicing and path planning for material deposition. The quality of fabricated HO is based on the sliced data. Slicing of 3D HO model requires geometric and material information in the object domain. Different slicing algorithms are extensively studied in rapid manufacturing community to address various issues e.g. minimizing the error in contours, optimizing slice thickness, improving surface finish, etc.

Conventional adaptive slicing methods produce unnecessary layers that contribute to increased fabrication time without improving the overall quality of the part surfaces. An approach was proposed by Tyberg [23] for adaptive slicing that significantly reduces fabrication time. The approach had been implemented on an FDM 1600 rapid prototyping system, and demonstrated 17-37% reduction in fabrication time compared to that of conventional slicing methods.

The layering error was reduced with smaller slice thickness. Variable thickness slicing methods are discussed for handling peaks, flat areas and staircase effects. Kulkarni [14] has developed an accurate slicing procedure for layered manufacturing while another researcher Sabourin [19] has proposed an adaptive high-precision exterior, high speed interior slicing procedure, based on the STL file. Commercial software MIMICS software was used to tailor properties of HO. Based on stress analysis, energy density was varied in selected regions to achieve reduced weight and cost.

The accuracy lost due to tessellation in MIMICS was avoided by using MATLAB as a tool. Retrieving the geometric and material information during slicing is a tedious task. Divesh [3] has highlighted the issues in the translation of CAD models to STL files for RP purposes. STL files of different tolerances and slice thicknesses were generated to study the effect of slice thickness on surface finish and build time. The layering error increases, and the surface finish quality and build time decreases, with increase in slice thickness.

VI. RESULTS AND DISCUSSION

In view of the above discussions, the following issues related to raid prototyping of HO are needed to be addressed:

- An adaptive slice generation procedure is required for rapid manufacturing of heterogeneous objects. Slicing errors should be reduced to the minimum, for better surface finish.
- Computing the optimum layer thickness is a tough task considering geometric and material variations.
- RP techniques need point wise diverse data i.e. geometric and material. It is a challenge to process the geometric and material information while slicing such a model into parallel sections. Effective data retrieval system is also needed for rapid manufacturing of HO. The proposed approach is capable to take care of these challenges and if implemented with generic heterogeneous object modeling approach is capable of fabrication multi-material objects especially function graded materials.

REFERENCES


