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Rapid Prototyping of Heterogeneous Objects: Issues and Challenges

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Abstract - **Heterogeneous objects (HO), composed of multiple materials, are now increasingly being used in engineering applications. With the development of a new fabrication method called Rapid Prototyping (RP), a new dimension is added to manufacture these objects. To manufacture heterogeneous object by RP, a CAD model is required that contains both geometric information as well as material information. Conventionally, most of the available CAD modelling software are able to save the 3D modelled object in the form of geometric and topologic data in stereo lithography file format and do not contain local information of the different materials or their composition in the object. So the conventional 3D modelling software can not be used for the fabrication of heterogeneous objects (HO) through rapid prototyping. The paper highlights all these issues and problems which arise for rapid prototyping of heterogeneous objects. The principles of rapid manufacturing for homogenous objects are discussed and various available RP techniques are explored. The procedure for rapid manufacturing of heterogeneous objects has been proposed. Various challenges and issues are highlighted. Finally, based on these issues, the objectives and scope for future work are identified.**

Keywords: **heterogeneous objects, rapid prototyping, CAD modelling**.

I.INTRODUCTION

Most of the conventional engineering parts are made up of homogeneous materials, having uniform composition throughout the object domain which could be a metal, composite or an alloy. In fact, the material domains for metal have uniform composition through out; while for alloys/composites, it is assumed that there is no variation in composition regardless of non-homogeneous character at a microscopic scale. With the advent of composition varying functional components, a variety of materials are introduced diversely in an object and such objects are termed as heterogeneous objects. Heterogeneous objects (HO) are, thus, composed of differently constituent materials with varying composition and/or microstructure. Heterogeneous objects are categorized as; multi-material objects with discrete material distribution, objects with sub-objects embedded and functionally graded materials (FGM) with continuous material distributions which are explained in Fig. 1. Since heterogeneous objects are perceived to be better than homogeneous objects in terms of combined mechanical, thermal and electrical properties of the preferred materials, thus, functionally efficient and cost reducing designs can be achieved within a single solid. Emerging technologies i.e. biomedical, geophysical and nano-scale modelling involve objects with multiple materials that results in required anisotropic properties across the object domain. In general, heterogeneous objects have key advantages in the applications where multi-fold functional requirements are expected.

Many structures components used in aerospace applications such as turbine blades [1], vanes and outer plane body etc. (as shown in Fig.2) require the material performances to vary continuously with the location within the component. It is advised to use FGM for making such components.

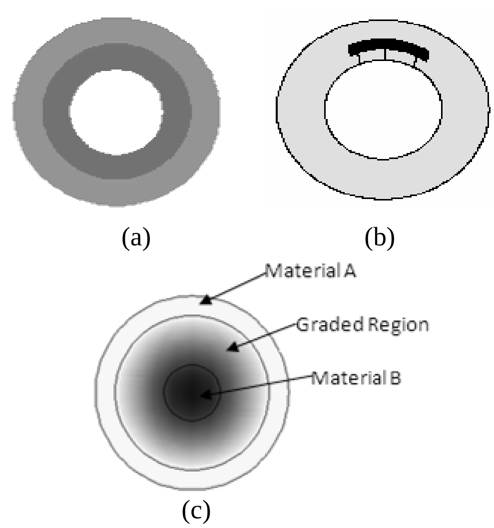

Fig.1 Three Categories of Heterogeneous Objects: (a) Multi-materials objects, (b) Objects with sub-objects embedded, and (c) Functionally Graded Materials (FGM)

FGMs provide compositionally graded layer pattern between the comprising materials so that the composition of materials can vary continuously, thus, allowing properties, such as heat resistance and mechanical strength, to have a smooth evolution from one location to another location.

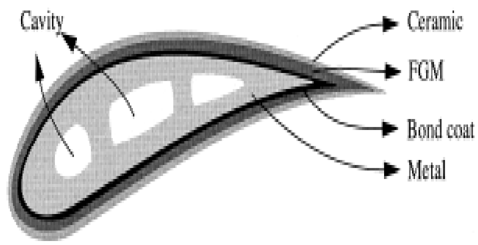

Fig. 2: Heterogeneous Turbine Blade [1]

With heterogeneous objects, the following objectives can be frequently achieved in comparison to homogeneous objects:

a. Anisotropic properties can be obtained.
b. Dissimilar properties and advantages of various materials can be achieved within a single object.
c. Conventional limitations which arise due to material boundaries such as stress concentration, fatigue, non-uniform thermal expansion etc. can be easily shunned or abolished with continuous material variations.

Due to these exceptional credentials and exclusive features, heterogeneous objects have found a number of application in various technical and non-technical fields in recent years. Extensive applications have been found in mechanical [2], [3], electrical [4], chemical [5], thermal [6], optical [7], bio-medical [8]-[10] and other relevant fields [11]-[14].

The wide applications of HO in diverse areas call for systematic approaches for design, modelling, analysis and fabrication of heterogeneous object. Modelling of HO requires additional information regarding distribution of materials along with the geometric information. Analysis of HO also needs information about multi-material composition at each point in the object domain. Additive (Rapid) manufacturing techniques can produce parts by depositing the materials layer by layer using 3D CAD model of the object. The few additive manufacturing techniques have capability to fabricate heterogeneous objects but they too require 3D heterogeneous CAD model.

So, the development of computer aided HO model and its utility in downward applications in design and manufacturing are important issues to realize the multi-fold functional components. The current work focuses on highlighting the issues and challenges for the rapid manufacturing of HO. The objectives in the field of modelling and rapid manufacturing of HO are defined in this paper. Section II introduces the principle of rapid manufacturing for homogenous objects and elaborates various available RP techniques. Section III introduces the rapid manufacturing of heterogeneous objects. The procedure for rapid manufacturing of heterogeneous objects is discussed in Section IV. Various challenges and issues which will inspire the futures research are discussed in Section V. Finally, based on these issues, the objectives and scope for future work are identified which in turn are presented in Section VI.

II.RAPID PROTOTYPING TECHNIQUES

Rapid Prototyping (RP) or rapid manufacturing may be defined as a technique invented to rapidly manufacture a model/prototype of an object or assembly using computer aided design (CAD) data of its three-dimensional geometric model. Now-a-days, a number of RP techniques are available in the market. Rapid Prototyping is one of the advance techniques for quick manufacturing/prototyping. In this (RP), the material is deposited layer by layer under various control mechanisms to produce a prototype. Conventional manufacturing (e.g. NC/CNC machining) is a 3D process, in which the material is removed from a work piece, thus is termed as subtractive manufacturing. In contrast, RP is a 2.5 D method and in most of these techniques, layers are stacked continuously as per the geometric information provided by the controller. A distinct advantage of creating a part layer by layer is that its complex geometry parts can be easily prototyped and thus has a considerably less impact on the manufacturing process.

Rapid prototyping technique is generally used for rapid fabrication of prototypes for designed functionality has application in fabricating patterns/molds, medical implants/bones, military components, consumer products etc. The RP is a direct fabrication process and does not require conventional tooling, fixturing and other supportive activities of conventional machining. It starts from the 3D CAD model of the object and create the prototype layer by layer in a very short time as comparison to hours of working in conventional machining.

Rapid Prototyping has also been named as solid free-form manufacturing; rapid manufacturing, and layered manufacturing. RP produced prototypes can be used for geometrical shape evaluation and real testing under designed loading conditions. RP techniques reduce the design time and improve the quality of the product. In some cases, the RP prototype can be considered as the final part, but normally the materials used in rapid prototyping are not strong and has lower surface finish. With the advent of new materials, the geometrically complex parts can be easily produced.

Rapid manufacturing processes can also be categorized into; subtractive manufacturing and additive manufacturing processes. Additive rapid manufacturing processes refer to the fabrication of prototypes layer by layer under computer control; thus, create a solid of predefined geometric shape as modelled in any 3D CAD software. The date from 3D CAD model is transferred to RP setup in the form of stereo lithography (.stl) file formats. The controller in the RP setup provides the cross-section information of the object and directs the mechanism to deposit the material at defined locations, thus built the part in very short time.

RP has many advantages when compared to conventional manufacturing methods, which are briefly discussed below:

a. Geometrically complex objects can be easily fabricated within very limited time.
b. Rapid prototyping is an economic process to produce prototypes as it does not involve arrangement of any product/process layout for the mere purpose of fabricating prototypes.
c. Re-designing/modifying/re-manufacturing an object is quite an easy task in rapid prototyping. Changes can be easily incorporated in the geometric model which facilitates the design optimization and also eliminates the chance of amendment at a later production stage. Thus, rapid prototyping techniques help to reduce design and product development costs and shorten lead time substantially as comparison to conventional manufacturing methods. Thus, RP considerably reduces new product development costs and the time to market.

For last twenty five years, a number of researchers has been contributed in the field of rapid prototyping and in particular, works on, data transfer, process planning and metal deposition. Industrial implementations of the rapid prototyping became available in the late 1980s with the stereo lithography machine by 3D systems of California. Since then, this industry has flourished and a partial list of current LM systems includes:

- Stereo lithography (SLA)
- Selective laser sintering (SLS)
- Fused Deposition Modelling (FDM)
- Solid Ground Curing(SGC)
- Laminated Object Manufacturing (LOM), etc.

III.RAPID MANUFACTURING OF HETEROGENEOUS OBJECTS

The basic principles of various available RP processes are either the identical or almost analogous. But, depending upon the applications, theses processes use different fabrication materials like, polymer, ceramic, wax, paper and different additive techniques like, sintering, binding, adhering, and solidifying.

Some of the above RP processes have capability to manufacture HO. As discussed above, researchers have been focusing on the vast applications of HO. These functional part scan be realized through rapid manufacturing processes. Conventionally, material information is not considered during modelling, 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 CAD model should be instinctive in demonstrating geometric, topological and material information simultaneously; capable of representing complex geometry objects; compact, accurate and compatible. This condition is an essential feature to successfully exchange data among design, analysis and manufacturing processes.

IV.PROCEDURE FOR RAPID MANUFACTURING OF HETEROGENEOUS OBJECTS

The procedure for rapid manufacturing of heterogeneous objects is described in Fig. 3. 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 modelled, 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 modellers 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 modelling 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 modelled 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.

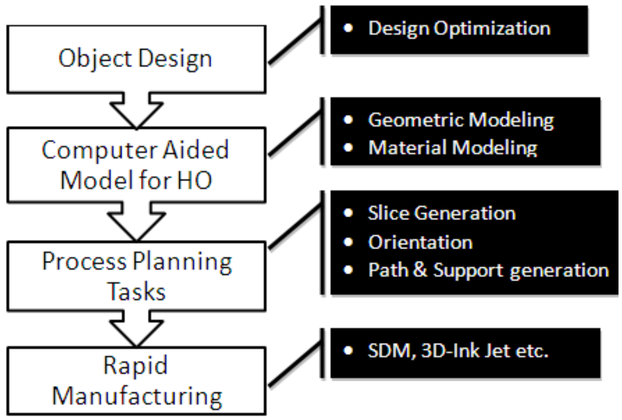

Fig. 3 Procedure for Rapid Prototyping of Heterogeneous Objects

Thus, computer aided model plays an important role in the object design and rapid manufacturing of heterogeneous objects [15]. 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.

V.ISSUES, GAPS AND CHALLENGES FOR THE WORK

The issues related to HO modelling, gaps in existing schemes and challenges motivating the future research are discussed in this section.

There are quite a few significant issues that motivate carrying out in-depth studies on heterogeneous object modelling, and in fact, make it an absolute necessity:

- Traditional CAD systems, used for conventional design method, can only represent the geometry and topology of an object. No material information is available within the conventional CAD representations, thus, they fail to represent a heterogeneous object.
- To the best of the knowledge, there has been no commercial CAD system for HO modelling and, thus, has created a bottleneck that prevents heterogeneous objects from wider applications.
- For rapid manufacturing of heterogeneous objects, the data for model transfer and slice representation needs to be retrieved directly from the 3D CAD model which should include both geometry and material information, and thus, there is a need of a generic and universally accepted modelling system.
- In finite element analysis (FEA), local material information must be derived from the heterogeneous models prior to carrying out further computations. Computer aided model should be able to convey this information for analysis of heterogeneous objects.
- Heterogeneous CAD models are the prerequisites for the downstream applications of analysis, fabrication and visualization of heterogeneous objects. Thus, the model should be able to communicate and share the data among analysis, fabrication and visualization modules.

Much effort has been dedicated to heterogeneous object modelling in the past. A number of theoretical representations, material function derivations and optimization techniques have been developed for heterogeneous object modelling. Despite these progresses, heterogeneous object modelling is still in its infancy and there are some gaps in existing literature that needs to be addressed properly by the research fraternity. These gaps are discussed as below [16]-[20]:

- Most of the existing computer aided models are insufficient to provide generic and uniform representations for heterogeneous objects. The work on complex geometric and material variations is limited, thus, modelling complex heterogeneous objects is still a challenge.
- Issues related to rapid manufacturing of HO e.g. optimizing the layer thickness considering geometric and material effects and retrieving material information during slice generation seeks more attention.
- The integration of effective HO computer aided modelling tools with visualization, analysis and rapid prototyping set-ups is limited. To the best of the knowledge, no research has been dedicated to provide an integrated platform for modelling, analysis, visualization and manufacturing of heterogeneous objects.
- System level research and development for successful implementation of computer aided models has not yet fully unearthed. The detailed system architecture, framework, visualizations, data communications and user interactions are either not paid due attention or assumed to be accomplished within the current homogeneous modelling environments.

Recent studies have shown that computer aided modelling for HO should be intuitive in representing geometric, topology and material information simultaneously; capable of representing complex solids; compact, exact and compatible. This is essential for exchange of data among design, analysis and manufacturing process plan domain. Developing a computer aided model for HO is a big challenge for engineering fraternity as the model is expected to be:

- capable of representing the geometry, topology and material information simultaneously, generically and uniformly;
- capable of providing intuitive modelling tools for heterogeneous object modelling, modification and maintenance;
- able to model complex heterogeneous objects, which are generally supposed to have simultaneous complex geometry intricacies and compound material variations;
- able to capture user's design intents, interpret user's interactions and generate faithful, high quality computer visualizations at interactive rate;
- capable of designing and analyzing physically manufacturable heterogeneous objects and offering convenient interfaces for functional evaluation and rapid prototyping.

VI.SCOPE AND OBJECTIVES FOR THE WORK

Although, in recent years, several schemes have appeared about the computer aided modelling of simple heterogeneous objects e.g. multi-material objects or one dimensional functionally graded materials (FGMs), relatively few have focused on modelling complex 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 modelling complex HO and integration with downstream applications of analysis and manufacturing. It is a big challenge for the engineering fraternity to resolve these issues and remove the gaps in existing representations. Thus, the development of a computer aided approach, which would achieve the reported challenges and enlarge the scope of heterogeneous object modelling for downstream applications, is seemed as an attractive proposition. Therefore, the scope of future work is extended to developing a generic and uniform computer aided approach for representing geometric and material information simultaneously and modelling complex HO. The scope of the future work can be further extended to effectively exchange the HO modelling data i.e. both geometric and material, for functional analysis, high quality visualizations and rapid manufacturing of HO. Resolving other issues related to design, analysis and rapid manufacturing of HO e.g. material distribution, slice generation, scan algorithm for geometry and material evaluation, and properties evaluation, etc. enlarge the scope of current work. Based on these scopes, the main objectives of possible future work are identified as below:

- The main objective of the work will be to develop a computer aided modelling schema for heterogeneous objects, by extending the mathematical models and computer data structures of the modern solid modelling techniques. The computer aided model should be uniform and generic, and capable of representing the geometry and material information simultaneously for downstream applications.
- As the computer aided model is a fundamental requirement for analysis, fabrication and visualization of heterogeneous objects, thus, the second objective will be to design and develop a system structure adept in linking the computer aided model with different modules necessary for design, analysis and rapid manufacturing of heterogeneous objects.
- The third objective will be to develop a slice generation procedure and layer thickness optimization method for heterogeneous objects considering geometry as well as material variation effects. The aim can be to develop an algorithm for material distribution and data retrieval during rapid manufacturing of heterogeneous object.
- The fourth scope for future work will be to develop a procedure for analysis of a heterogeneous object using finite element method (FEM), for the verification of data communication among modelling and analysis modules.

VII.CONCLUSION

The paper successfully reviewed various available rapid prototyping techniques. The principle of rapid manufacturing for homogenous objects had been elaborated. The advent of heterogeneous objects had been discussed with advance applications. The novelty of the paper was to propose the procedure for rapid manufacturing of heterogeneous objects. The procedure provided the algorithm to include material information along the geometrical and topologic information in a 3D CAD model of a heterogeneous object. The issues related to HO modelling, deficiencies of existing schemes and challenges fascinating the fabrication of future heterogeneous objects had been established. Finally, the objectives and scope for future work for effectively HO modelling, analysis, visualization and rapid manufacturing of HO had been defined.

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