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ScienceDirect

Acta Astronautica 61 (2007) 352 – 359

ACTA ASTRONAUTICA

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New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation

P. Rochus[a,*], J.-Y. Plesseria[a], M. Van Elsen[b], J.-P. Kruth[b], R. Carrus[c], T. Dormal[c]

[a]Centre Spatial de Liège (CSL), Université de Liège, av. du Pré Aily, 4031 Angleur, Belgium
[b]Katholieke Universiteit Leuven (KUL), Division PMA, Celestijnenlaan 300B, 3001 Heverlee, Belgium
[c]Crif, Liege Science Park, Rue Bois Saint-Jean 12, B-4102 Seraing, Belgium

Available online 27 March 2007

Abstract

In the frame of a research project, CRIF, KUL and CSL have investigated the possibility to use rapid prototyping and rapid manufacturing (RP/RM) techniques during space instrument development. Rapid prototyping and rapid manufacturing terms gather several techniques with the common baseline that parts are built layer by layer, starting from a CAD model. These techniques imply powder, paste or liquid and are applicable to polymers, ceramics and metals.

In a first step, the major advantages of these techniques have been presented to Belgian industries implied in the space sector and, as a result of the discussions, development goals for the project have been identified. Several types of use have also been pointed, from demonstration mock-up to real space hardware.

In parallel to technical developments, several case studies and tests have been performed. The case studies have shown that the rapid manufacturing allows complex geometries to be created. A drastic decrease of the number of separate parts and bolted junctions ease the predictability of the mechanical and thermal behaviour and limit the risk of imperfect junction.

As a result of the project, a guidelines document has been issued to give as much information as possible on how to perform a space instrument design using the advantages of RP/RM techniques.

1. Introduction

Rapid prototyping and manufacturing are known to be disruptive technologies. In the last years, industrial use of these methods has grown rapidly and in parallel the processes are improving everyday [1,2]. Several Belgian research centres are largely implied in these developments.

Rapid manufacturing and rapid prototyping are applying the principle of manufacturing parts layer by layer starting from liquid, paste or powder. After a layer of material is deposited, the selected surface is treated according to a process defined by the chosen technique in order to solidify a cross-section of the final component.

These techniques allow a different way of designing since the manufacturing constraints are completely different from classical manufacturing. These processes are already applied for prototyping, small series, injection moulds manufacturing, mock-ups and are used in several engineering sectors.

The goal of this project was to find new applications of this process in the space instrumentation field. This required two steps: On the one hand, the advantages of RP/RM were explained to space instrument designers

* Corresponding author.
E-mail addresses: prochus@ulg.ac.be (P. Rochus), jyplesseria@ulg.ac.be (J.-Y. Plesseria), jean-pierre.kruth@mech.kuleuven.be (J.-P. Kruth), raoul.carrus@crif.be (R. Carrus), thierry.dormal@crif.be (T. Dormal).

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doi:10.1016/j.actaastro.2007.01.004

and possible applications were investigated. On the other hand, it was necessary for the process developers to define the specific requirements for space instruments.

In order to run this project, two groups were set, the partner group gathering CRIF, KUL (developers) and CSL (user) and the user committee gathering most of the Belgian industries working in the space sector or applying RP/RM.

2. Rapid manufacturing/prototyping

2.1. General description

The technique starts with a 3D CAD model of the part to build. This model is converted by software in a series of layers.

This series of layer is transferred to the building machine. The layers are then "printed" in the material by different kinds of processes summarised here under. After a layer is "printed", a new layer of material is deposited on top and the next layer is "printed". Depending on the process, a post-processing may be required.

2.2. Stereolithography (SLA)

Basic SLA is applied in liquid state. The liquid used are UV curable polymers. An ultra violet laser is used to cure the polymer layer by layer. The obtained material is usually not usable as engineering material but can nevertheless be used for mock-up and lightweight covers. An important variant of this process is based on paste polymer (optoform process). The advantage is that this paste can be filled with solid reinforcement (metal or ceramic powder for example). Further treatment (debinding) can also remove completely the original binder component to only keep the metal or the ceramic.

2.3. Selective laser sintering/melting (SLS/SLM)

The laser sintering process can be applied to a polymer or metallic powder [3]. The solidification is obtained by heat input from a laser, causing a solid state sintering or melting of the powder material. The basic process of SLS uses a pure polymeric powder. A ceramic material can be added to improve the mechanical properties. Because older laser systems had not enough power to melt high-end metal materials, SLS was developed to process a powder mixture containing a low melting material and a high melting material. The process is called SLS if the low melting material is polymeric and direct metal laser melting (DMLS) if that material is a low melting metallic powder (e.g. cupper). Only the low melting material is molten ensuring the cohesion of the built part (called green part) by wetting the high melting point material. Further treatment is performed in a furnace (debinding and infiltration) for SLS. With DMLS, there is no additional post processing required. The resulting part is a mixture of two alloys.

A variant of the technique is SLM. This time there is only one kind of metal powder and it is directly melted by the laser. By this method a density higher than 99.5% can be obtained directly [4] for commercial engineering materials like stainless steel, titanium alloys and aluminium alloys.

2.4. Jet based technologies

(a) *3D printing*: In this kind of method, a laser is no more required. The powder cohesion is ensured by the deposition of a binder by a system looking like an inkjet-type printer. After each layer, curing of the binder is performed.

The obtained green part is put in a furnace for binder removal. Further processes allow increasing the density by infiltration of a filler material or by solid state sintering.

(b) *Laser cladding*: Laser cladding has the particularity to inject directly the powder in the laser beam spot. Using several injection nozzles, different materials can be used in the same part. This technique was not tested during the project but is mentioned for completeness.

3. Applicability to space

3.1. Prototyping

The first use can be basic prototyping. At early stages of projects, scale models can be required to verify implementation of different elements. Rapid prototyping allows a quasi direct link between CAD models and reality.

3.2. Mock-up

Sometime, some parts of an instrument need to be geometrically represented in a development model. In order to simplify the manufacturing of these pieces of lower interest, rapid prototyping can be used.

Full mock-ups of instruments are also sometimes required to ease the design and preparation of electrical harnesses or thermal insulation (MLI). Rapid prototyping allows using 3D models directly coming from the design office without need for detailed drawings and long assembly steps.

3.3. Test articles

Again, during testing and qualification of an instrument, some lower interest parts can be built by rapid manufacturing. Ground support equipment can also be provided by rapid manufacturing.

3.4. Real flight hardware

The ultimate goal of the project was to show that we can use rapid manufacturing for flying parts. The recommendations given by the users were mainly in that goal, knowing that these will also apply for all the previous uses. The implementation in space hardware will probably be done in two steps: non-structural parts followed by structural parts.

(a) *Non-structural parts*: The non-structural parts are the easiest to introduce. Mechanical properties are less critical and several current materials (including polymers) can already be used. The advantages of rapid manufacturing can be used for covers, small frames, complex parts, etc.

(b) *Structural parts*: Taking advantage of the allowed complexity of parts, structural parts can be built including several functionalities in small volumes.

4. Space requirements

4.1. Definition

"Space requirements", as they were named in this project, is a quite generic term that hides two parts. First, there are basic requirements on the materials that must be checked, being cleanliness, vacuum resistance, radiation resistance (not checked in this project). A second part was mainly including a list of needs that are classical for space applications, for example the need for mass saving, good knowledge of properties, predictability. In this part, the users also recommended some specific materials to be investigated as titanium, aluminium and silicon carbide.

4.2. Cleanliness and vacuum resistance

For this point, the ECSS standard has been applied to different classical materials of RP/RM. A first set of tests has been performed in CSL facilities. They show good results of the polymers and allow a pre-selection of the most promising materials. A reduced number of samples have then been sent to ESA laboratory in ESTEC for a complete test. All four samples passed the test successfully.

4.3. Needs

Having seen the capabilities of the rapid manufacturing process, comments have been given by the user group. These comments were mainly concerning the density, accuracy and lightweight materials. Full density is mandatory in space material to avoid contamination that can be trapped in the porosities. This contamination is difficult to remove a priori and also difficult to prevent. Accuracy is the main problem of rapid manufacturing because the building process implies the use of local thermo-dynamical/chemical process which envelope is not easily defined and localised. The materials that are often used in space are aluminium, titanium and SiC. These materials are known to be possible material for RP/RM but only little effort was made up to now to develop them.

5. Main achievements of the project

5.1. Improvement of techniques

The users gave different challenges to the developers through case studies. To fulfil the demand, CRIF and KUL have improved their techniques. Large dimensions parts have been done and bounding techniques for space application of parts have been investigated. High to full density materials have been obtained by different techniques. "Printing" techniques have been improved by updating laser performances, establishing in situ process control, adapting binder and powder characteristics.

Accuracy has in general improved for several techniques and construction of lightweight structure (comparable to 3D honeycomb) has been shown to be feasible (even if not optimised in the frame of this project) [5].

5.2. Evaluation of new materials

Titanium was the first material to be investigated because of the compatibility with the current machines at KUL. Titanium is treated by SLM allowing a nearly full density ($>99.9\%$). Some drawbacks have been found concerning the freedom of shapes that can be manufactured and residual stresses [6]. Nevertheless, some rules have been established for the first users of this material. Developments are in progress to solve the current difficulties of the technique.

Aluminium was not evaluated in the current project due to the safety problems with aluminium powders but RP/RM with aluminium is known to be feasible.

Some small grain size powders (called nanopowder) were investigated during the project showing a better accuracy and a softer surface finish. This material needs to be further investigated.

Some exploration was also made for the SiC powder. Some methods for RM/RP with SiC powder are under development.

5.3. Exploration of 3D lightweight structures

In order to avoid excessive mass and decrease the "printing" time for one layer, the use of internal structure is already used often. During this project, we investigated the possibility to use more optimised internal structure. By the same way that a honeycomb panel has very good properties for a low mass, some equivalent 3D structure can be used in volumes (see [7–10] for the expected properties). Different basic cells shapes have been used and it showed to be feasible [5]. The first limitation is that it is necessary to think about powder/paste removal in the definition of the cells. The second difficulty is the size of the CAD files required to define the internal structure. As the cells are not yet known as a repetitive filling structure for the software, the entire detailed geometry is stored in the file (Fig. 1).

These studies stayed at an early phase since no mechanical optimisation of the cell shape was performed. It is obviously linked to the actual external geometry and must be adapted on a case by case method (optimisation is possible; see [11,12]); we could even imagine to extend these theories to include variable porosity and variable composition).

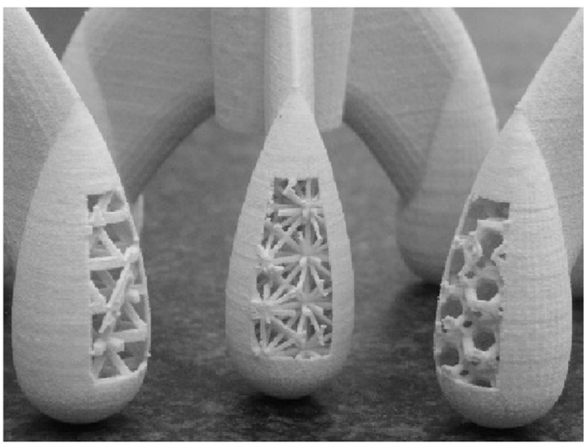

Fig. 1. Different 3D structure inside a volumic part.

5.4. Case studies

The user committee was very eager to propose case studies for this project and from the original 1 case planned, we finally realised 13 of them. All did not reach the same final achievement (between CAD evaluations of feasibility to final integration in real set-up) but all brings us a lot of information. Several case studies concern designs that are user's properties but two will be presented here (see Section 6).

5.5. Guideline establishment

As a result of these three years of research, a guideline document has been written for the user committee in order to give them the knowledge of the techniques and the best way to use them. These guidelines include the different experiences coming from the case studies as well as a summary of the current available techniques and materials. This document is kept open so that it will continue to be updated with future input from the different groups.

6. Examples of case studies

6.1. A high rejection cooled collimator

(a) *Description*: For an instrumentation project, a test set-up was prepared to measure high efficiency straylight baffle. For this measurement, a laser collimator was required. It was designed to collimate the light of a powerful laser coming out of a fibre. The part of the fibre output power not collected by the lens, had to be absorbed by the internal walls of the collimator and evacuated.

(b) *Original design*: The original design included 13 parts that had to be integrated and aligned together. A copper cooling pipe was brazed on the outer surface to collect the power and evacuate it (Fig. 2).

(c) *Adaptation to RM*: The design of the collimator was re-optimised taking into account the RM possibilities. All internal baffles were included and adapted exactly to the optical beam. The cooling pipe was directly included in the wall and concentrated in the area where the power would be mainly concentrated. The resulting collimator consists of only two parts. To have the correct accuracy of the placement of the optical elements, the lens seal was re-machined afterwards (Fig. 3).

(d) *Results*: The obtained part was manufactured using DMLS process and integrated in the test set-up. The results obtained are very good and this new

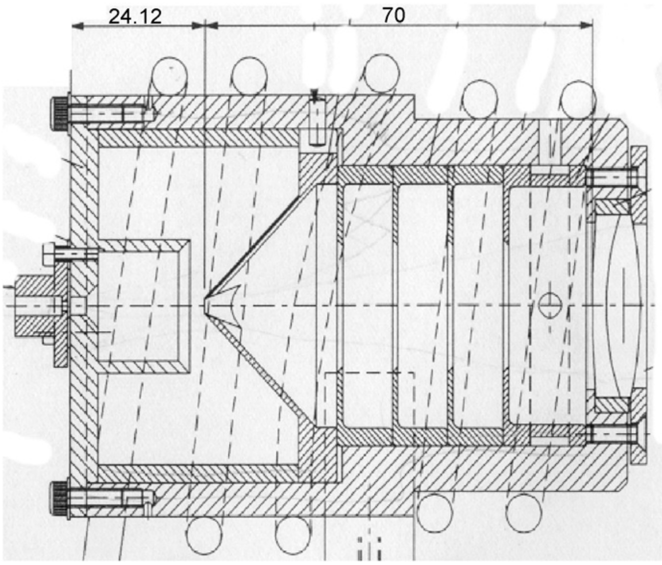

Fig. 2. Original design of the collimator.

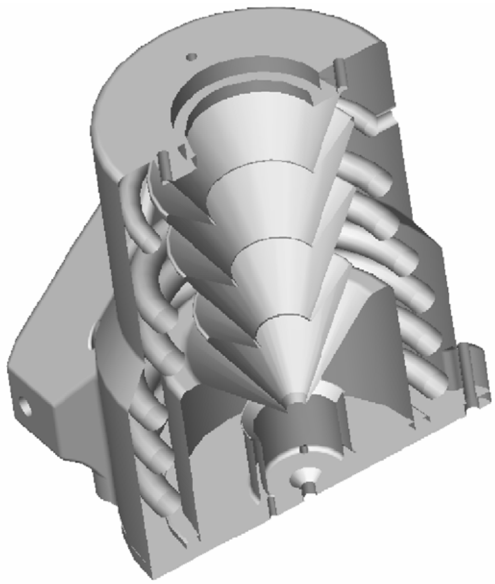

Fig. 3. Collimator design for RM.

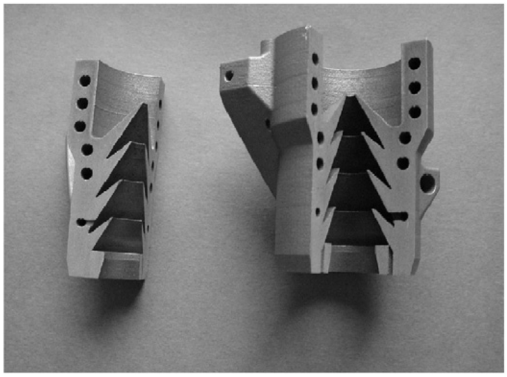

Fig. 4. Final collimator (cut after manufacturing for demonstration purpose).

collimator was kept as the baseline for the following straylight measurements (Fig. 4).

6.2. A full scale model of an optical instrument

(a) *Introduction*: An instrument is under development in CSL for the James Webb Space Telescope (JWST). This instrument is the input optics and calibration (IOC) unit for the Mid InfraRed Instrument (MIRI). In the frame of the MIRI development, a structural and thermal model (STM) had to be manufactured for system tests of the primary structure. For that, an IOC STM was designed, manufactured and delivered. It was decided to re-manufacture this STM using RM techniques and materials and to perform some mechanical analyses and testing.

(b) *Design*: The original design was kept but simplified, all the bolted junctions were removed and the number of parts was decreased. The selected material is tooling B, an epoxy material filled with silica developed for the optoform process.

Due to the large size of the instrument with respect to the RM tools available, it was decided to cut it in

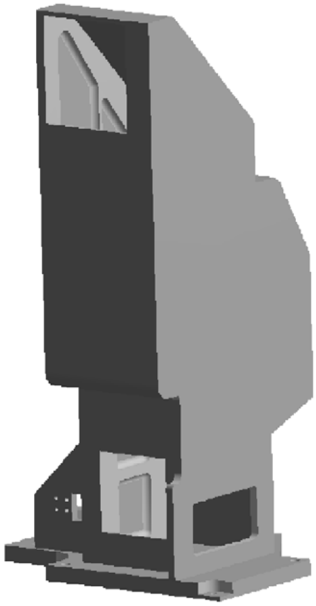

Fig. 5. Design updated for RM.

three main parts. Vacuum compatible glue was tested on samples of the same material to check that the assembly of the parts could be done safely. All samples showed that the adhesion of the glue to the material was fine and that the glue mechanical performances were at least better than the base material (Fig. 5).

(c) *Mechanical analyses*: The modified design for RM was used for mechanical analysis. The goal of the analyses was to perform eigenfrequency prediction and resistance to quasistatic loads.

The first eigenfrequency was found at 136 Hz what is, as expected, lower than the aluminium structure (189 Hz). This is due to the lower stiffness of the selected material compensated by the lighter mass and the lower centre of gravity.

The resistance to 20 g quasistatic acceleration (sine qualification level for the IOC) has been checked and margins of safety were found positive (Fig. 6).

(d) *Mechanical tests*: Based on the positive results of the mechanical analyses, the vibration test could be performed. A vibration jig already used for the aluminium structure has been re-used. Instrumentation consisted in two three-axis accelerometers, one located at the top and one located in the middle.

The first low level runs showed good correlation with the predicted frequency but with a higher than expected amplification. The damping factor measured for the main modes was of the order of 1% (to be compared with the classical 2% taken for aluminium structures). So for safety reason we performed the high level tests by notching the top accelerometer acceleration to 24 g in order to limit the acceleration viewed by the instrument. A final run was performed without notching.

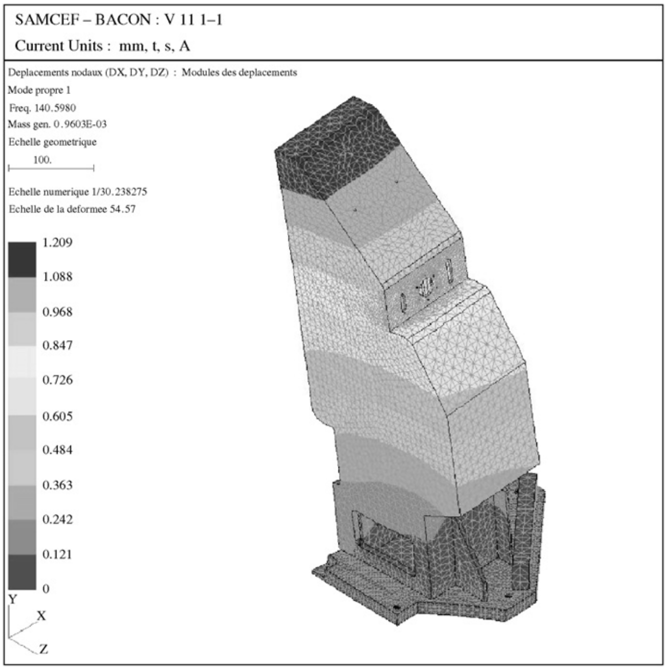

Fig. 6. First computed mode.

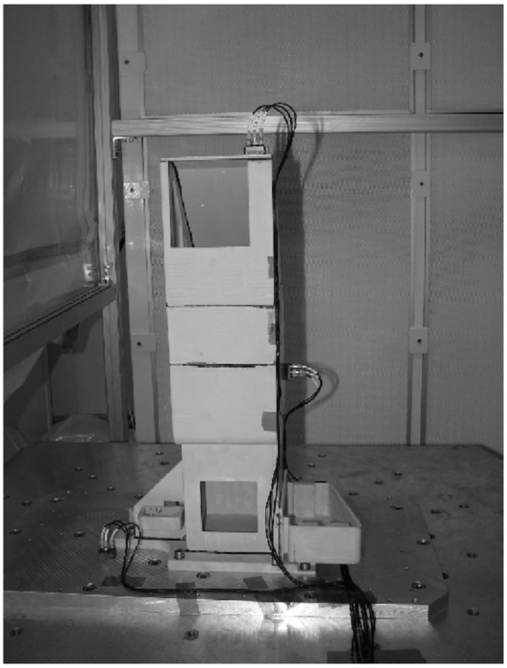

Fig. 7. IOC on the shaker.

The RM built IOC showed perfect resistance to the 20 g environment (no shift of eigenfrequency, no damages observed) (Fig. 7).

(e) *Tests results*: The test results are given in Table 1.

(f) *Model correlation*: Some correlation has been performed on the model to fit with the results. Responses have been computed at the location of the accelerometers and some parameters have been tuned, including the Young modulus, the mesh accuracy, the damping coefficient and the screw modelling. A very good correspondence has been found for the modes up to 1000 Hz. The quite low damping coefficient (around 1%) is probably due to the reduced number of components and the good joining. This is common to improved manufacturing techniques which often produce very good joints in structures reducing the amount of natural damping in structures. For instance, removing welds in bladed disc assemblies caused increased blade fatigue because of the reduced damping.

7. Conclusion

After this 3-years project, several developments have been performed in RP/RM techniques in order to make them applicable to space sector.

Several case studies have been performed in collaboration with Belgian industries allowing a close collaboration between the developers and the users. Guidelines have been written for the users to gather the information necessary to make good use of the techniques.

Even if this first project let several points open, a close relationship has been established between all the actors in Belgium to allow further development through future research projects or in real application.

Since the obtained results were very encouraging and industrial partners were enthusiastic, we have proposed to pursue the study on the theme of reliability of rapid manufacturing and on new materials (Ti, Al, SiC, CFRP). With the RM tools, producing porous and topological optimised parts can become a realizable reality due to the possible complexity of the outcome geometry. Topological optimisation could even be extended to materials with variable composition. Porous or hollow lightweight components, porous infiltrated parts could be studied. Hollow structures with varying the porosity or varying the composition to realise functionally graded materials, should also be possible, when the process will be fully controlled.

Concerning the materials, we will investigate different type of titanium and aluminium alloys (with different powder granulometry). New space materials such as silicon carbide, metal ceramic composites (SiC/Alu, ferrous materials with SiC), and carbon fibre reinforced polymer (CFRP), reveal themselves very efficient for

Table 1
Comparison of tests and FEM results

Frequency (Hz)	Observed direction	Equivalent mode number	Frequency at FEM (Hz)	Direction (Max Meff)	Difference (Hz (%))
136.8	Z	1°	136.4	Z	0.4 (0.3)
145.9	X	2°	150.1	X	4.2 (2.9)
310.6	θY	3°	351.5	θY	40.9 (13.2)
381.2	Z	–	–	–	–
554.6	X	4°	541.7	X	12.9 (2.3)
584.6	X	5°	569.6	X	15 (2.6)

many spacecraft structures like mirrors, structural panels, optical benches.

Acknowledgement

We want to acknowledge all the members of the user community that showed high interest in the project and give us a full support in the developments.

This project was funded by BELSPO in the frame of a Technological Attraction Pole project.

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