Lightweight nodal parts for large space truss structures enabled by SLM: modelling, manufacturing, and testing

E Golubev1,2, M Arkhipov1, A Galinovsky2 and A Klem1,2
1 Astro Space Center of Lebedev Physical Institute of Russian Academy of Sciences, 53 Leninskiy prospect, Moscow, 119991, Russia
2 Bauman Moscow State Technical University, 5/1 Baumanskaya 2-ya str., Moscow, 105005, Russia
E-mail: golubev.ev@asc.rssi.ru

Abstract. Selective laser melting (SLM), as a method of metal additive manufacturing, has developed rapidly over the last years to become a breakthrough technology capable of upending the way that products from aerospace and other various industrial sectors are not only fabricated but also designed. The purpose of this paper is to investigate the potential benefits and drawbacks of SLM implementation in the frame of design and development of components for large space lightweight structures. The three types of the most common structural engineering solutions are compared, based on the different manufacturing techniques and materials. The paper describes the results of the measurement of the shape of fittings after fabrication and cryogenic temperature-cycle tests. An extra option for the weight reduction of structures is given via the implementation of the topology optimization method. Three challenges have been identified, including quality of surfaces, deviation of geometry, residual internal stresses. This work shows the possibility to solve this topical issue by using a waterjet inspection technique and represents one of the first attempts for its implementation to perform a fast evaluation of mechanical properties of structural materials manufactured using SLM.

1. Introduction
Lattice or truss frameworks are widely utilized in the design of contemporary large space lightweight structures thanks to their excellent structural strength to weight ratio. Fittings that connect truss members in nodes have rather complex cross-sections and hence are difficult to manufacture. Connecting fittings for such structures made of metal alloys can be developed and manufactured using conventional machining methods [1]. However, fittings can represent up to 60% of the total truss weight. Therefore, the application of additive technologies allows to significantly expand development options of creating more efficient fitting structures [2].

The use of additive technologies for manufacturing fittings was studied based on the frame structure of the primary mirror of the space telescope “Millimetron” [3]. Its load-bearing frame is a complex 3D truss consisting of carbon fibre tubes and connecting fittings. A general view of the primary mirror’s structural engineering model is shown in figure 1. This structure is defined by a series of requirements, such as maximum rigidity and shape stability, high requirements for manufacturing and assembly accuracy, extremely low operating temperatures (up to 20K), a large number of part form factors, and their total quantity. All these searches for new engineering and design solutions a very topical issue.

This paper presents a study of the possibilities of using SLM for manufacturing truss fittings, a comparison with other competing technologies, and the results of experiments to verify key quality parameters.
2. Literature Review

2.1. Benefits and drawbacks of selective laser melting

Selective laser melting (SLM) is one of additive technologies, which has been actively developed during the last two decades. However, while other additive technologies used for prototyping, cast pattern and mould manufacturing have been firmly established in the industry, the list of the potential applications of SLM technologies as the suitable manufacturing method is still only being studied [2, 4]. This is caused both by the benefits and drawbacks of this approach.

Firstly, there is a prohibitively high level of geometrical complexity of parts, including thin-walled structures with interior cavities. Secondly, there is a wide range of metal powders: heat resistant and corrosion-resistant steels, aluminium, and titanium alloys. Thirdly, the selective laser melting is characterized by zero waste manufacturing (excluding a certain number of removable manufacturing supports), because unused powder can be reused. Furthermore, the physical and mechanical properties of manufactured material match those of conventional semi-finished products (rolled and forged products) [5, 6]. In addition, SLM tools with the capacity for building larger products (up to 500x500x500 mm) are now available, also there are many ongoing research projects aimed at increasing dimensions of manufactured parts. What is more, several parts can be built simultaneously, so long as they fit in the build chamber. Finally, many authors see this approach as a way to reduce the cost of parts and assemblies [7, 8].

However, nowadays there are quite a few drawbacks. Firstly, that is the high probability of shape warping as-fabricated SLM-built parts. This issue is caused by high thermal gradients during SLM process that leads to thermal deformations and residual stresses [9, 10]. Then, the modern manufacturing method as SLM requires the rapid and reliable quality control methods of produced parts. Further, we address both of these issues in this paper.

2.2. Waterjet inspection technique as the quality control method of SLM produced parts

Papers [11-16] substantiate the need for adequate information and diagnostics support using non-destructive inspection methods to control the quality of parts manufactured using additive technologies, in particular, selective laser melting (SLM). However, the issue of rapid determination of heterogeneity of mechanical properties of such materials remains unsolved. Therefore, the problem of fast evaluation of the heterogeneity of mechanical properties of structural materials manufactured using SLM is very
topical, since the quality of work surface of products made of such materials usually defines operating parameters.

In this study, waterjet inspection technique (WIT) was chosen as a non-destructive testing method. It is based on the scouring along some path impact of a high-speed water jet on the surface of the controlled object [17]. Upon that, the geometrical parameters of the formed erosive cavity serve as the informative attributes of diagnostics. The studies [18-19] present some of the results of experiments that demonstrate the capabilities of assessing homogeneity of the material. It shows the dependence between the depth of the cavity formed after waterjet impact and the hardness, impact viscosity of a material. This opens up the possibility of performing a detailed analysis of mechanical properties of SLM manufactured products, where the heterogeneity of mechanical properties often limits operating and structural reliability [20, 21]. Thus, we experimentally sampled this technique based on manufactured prototypes.

3. Experimental design

3.1. Search for structural engineering solutions

This paper analyses potential structural engineering solutions (figure 2). The carbon fibre fitting is characterized by low weight and is manufactured from a material with qualities close to those of the tube material (because another reinforcement method is used), which is especially important for coefficients of thermal expansion of various materials due to the deep cooling of the structure and the need to minimize thermal deformations. However, a significant drawback of this option is an extremely high price because of, primarily, the price of tooling required for a composite structure with complex geometry.

![Figure 2](image)

Figure 2. Examined Structural Engineering Solutions for Fittings: (a) carbon fibre fitting; (b) machined fitting; and (c) fitting manufactured using SLM.

The machined fitting (figure 2, b) was used to create a structural engineering mock-up (figure 1). The fitting has a modular design. Its threaded elements allow for a certain adjustment of the length of truss members during assembly to improve accuracy. The key drawback of this structure is large weight of the fitting, which leads to the combined weight of fittings in the frame structure reaching 60% of the total weight. It also negatively influences the level of thermal deformations of the structure during deep cooling.

Fitting No. 3 (figure 2, c) is manufactured using the SLM method with the Concept Laser M2 Cusing printer out of corrosion-resistant steel dust powder (the domestic analogue is 12X18H10T).

3.2. Manufacturing prototypes

The SLM-built fitting prototype proved acceptable manufacturability and cost of production. Thus, five fitting prototypes were made from Ti-6Al-4V titanium alloy using a Concept Laser M2 SLM machine (figure 3). Figure 4 shows four fittings connected in a closed member of the frame. The fifth prototype was designed for cryogenic testing. Due to manufacturing restrictions, the thickness of fitting walls was
increased to 1 mm, while the thickness limited by strength requirements is 0.8 mm. The weight of finished parts was 14-22 g, while the weight of the machined fitting (figure 2, b) was 79 g.

![Figure 3. SLM-built fittings from Ti-6Al-4V alloy.](image1)

![Figure 4. The prototype of the assembled petal frame segment.](image2)

### 3.3. Measurement of manufacturing errors

In order to measure the manufacturing errors, high precision geometry scanning was used [22]. The geometry of the produced fittings was measured at room temperature using the optical scanner ATOS III, with an accuracy of ±6 μm. The scan data was overlaid on the reference CAD model using a Gaussian best fit approach realized in the commercial software Geomagic Control®. The deviation analysis provided clarity that the accuracy of the SLM-built fittings was within ±0.1 mm of the reference geometry. Figure 5 shows the deviation colour map and table 1 gives calculated root-mean-square deviations (RMS) for the surface and the deviations of the axes of cylindrical surfaces (interfaces for truss members from CFRP tubes).

| Fitting No. | RMS (mm) | Axes deviation (degrees) |
|-------------|----------|-------------------------|
| No. 1       | 0.074    | ≤1.2°                   |
| No. 2       | 0.082    | ≤1.5°                   |
| No. 3       | 0.084    | ≤2.4°                   |

![Figure 5. Deviation Map (mm, relative to the reference CAD-geometry).](image3)

Given the fact that the considered frame structure operates at the temperature of 20K and exposed to almost 300 K temperature range, the issue of thermal dimensional stability is essential. According to the requirements, the thermal distortions of the primary mirror frame structure should not exceed 2 mm. In order to measure the residual thermal distortions of the frame structure, a cryogenic test was...
performed. For this test the specimen, which represents a section of the frame structure, was assembled from fitting No. 5 and CFRP tubes by an adhesive of cryogenic operation. During the first cryogenic thermal cycling, the specimen was cooled down to -195°C. Geometry was measured before and after cooling. Figure 7 shows measurement results – comparison of tube axes position before and after the cryogenic test. The maximum deviation of the tube axis was 0.12 degrees that fully meets the requirements for the dimensional stability of the truss.

3.4. Using topological optimization methods to minimize fitting structural weight

Using SLM to manufacture the fittings helped reduce the structural weight to less than 3 times the weight of the machined fitting and save 57% of the overall weight for the complete assembly. Additionally, the possibility of structural weight reduction using topological optimization based on computational modelling was investigated [23]. The optimization objective function was the minimum weight of the fitting with the constraints of required mechanical strength and rigidity. The boundary conditions for the static analysis were the loads emerging in the frame when it is delivered to outer space on a rocket. Figure 8 compares the initial geometry of fitting No. 1 and the so-called “biomorphic” optimized structure. It appeared that topological optimization enabled a weight reduction of the optimized area by an extra 34%, while the total weight of the fitting was reduced by 9%. As a result, the level of maximum stress in the structure fell by 21%.

Figure 6. Specimen for the Cryogenic Test.  
Figure 7. Comparison of Tube Alignment Before and After Cooling.  

Figure 8. Comparison of two fitting variants: (a) reference variant; (b) optimized variant.
3.5. **Waterjet inspection of fitting**

The WIT method for identifying the degree of the heterogeneity of an SLM-built material is based on the assumption that the mechanical properties change with a period equal to the step of the laser beam or the thickness of the growth. It follows that the regions of a material having lower mechanical properties as hardness or strength are subjected to greater erosion. A diagram of the formation of a microrelief of the cavity on the studied surface under the action of the waterjet is shown in figure 9.

![Diagram of Waterjet Inspection](image)

Figure 9. Scheme of WIT of the surface of SLM-built material.

4. **Results and discussion**

The WIT procedure was carried out using the abrasive waterjet cutting equipment Multicam WaterJet (US). One of the fittings has been exposed to the waterjet along its growth direction (figure 10). The following operating parameters were used: pump pressure – 350 MPa, waterjet traverse speed – 2 mm/s, stand-off distance – 5 mm. Pure water-jet was applied at the right angle to the surface. The image of the waterjet footprint was obtained using the laser scanning confocal microscope Carl Zeiss LSM 700.

![Image of Fitting](image)

Figure 10. Fitting after WIT test.

Figure 11 shows the results of the laser scanning of microrelief of waterjet footprint (or cavity) and its post-processing analysis. The standard Fourier analysis method was used via MATLAB for a detailed consideration of the informative parameters of the cavity. Fourier analysis spectrogram identifies dominant harmonic, its amplitude, and period. These are the characteristic of geometric deviations of waterjet footprint, which are due to periodic changes in mechanical properties along the cavity. It follows from the data in figure 11 that the dominant harmonic of the Fourier analysis of the cavity microrelief has a similar character to the geometry of laser melting of the material (the step between melt pools).

At the next step of experimental study, in order to verify the results of WIT, measurements of the surface microhardness were carried out parallel to the formed cavities. Based on the data obtained on the microrelief of the waterjet footprint and on the approximation of the microhardness measurement in the selected areas (600 μm in length), their correspondence and satisfactory correlation were established.

Thereby, the waterjet inspection technique shows sensitivity to variations in the mechanical properties (i.e. microhardness) of the SLM-built material with periodic dependence. That makes this method is perspective to develop for rapid determination of the degree of heterogeneity of materials and parts produced by SLM. Undoubtedly, it requires further study and comparison with other non-destructive inspection methods.
5. Conclusions

Based on the study results outlined above, we can draw the following conclusions:

1. The layered selective laser melting technology is efficient for manufacturing parts with complex profiles, such as truss fittings. Conventional technologies (casting, machining) cannot provide the same level of structural strength and low weight.

2. Satisfactory manufacturing accuracy was achieved. Accuracy can be improved by different building orientation and using manufacturing supports.

3. The possibility to use SLM manufactured products in cryogenic equipment together with carbon fibre parts was confirmed.

4. Topological optimization methods efficiently complement the potential of additive technologies in reducing the structural weight of load-bearing elements. However, they require significant computational costs and time to post-process obtained “biomorphic” geometry.

5. Waterjet inspection technique has shown itself to be sensitive to variations in the mechanical properties of the SLM-built material with periodic dependence. It requires further study and the comparison with other non-destructive inspection methods.

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