

# Implementation of metal 3D-printing in manufacturing navigation systems: the results of practical studies

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**Abstract.** Practical investigation results of metal 3D-printing of parts are presented. Surface roughness, dimensional repeatability, and porosity of produced specimens are measured. Machinability, tensile strength, as well as cost efficiency of parts are evaluated. Based on the obtained results, a conclusion about implementation of metal 3D-printing in navigation systems manufacturing is made.

## Introduction

The main feature of the first navigation systems was a gimbal, which had the following features: precision torque motors and angle sensors, accurate bearing supports, and perfect slip rings. These features provide data and signal exchange while the gimbal rings perform accurate rotation to 360 degrees with the lowest frictional force. As a result of the features merging, the gimbal rings have significantly complicated the geometry. Over the 20<sup>th</sup> century, the only technology that provided manufacturing of those gimbals was casting. Therefore, the design methodology of navigation systems was developing based on casting. As a result, besides the gimbal rings, a lot of non-crucial parts were manufactured by casting. Since the machines with computer numerical control (CNC) appeared, it has been possible to avoid environmentally harmful cast manufacturing in some cases, but not always. Moreover, great technological possibilities of CNC machining have determined the next step of advancement of navigation systems manufacturing towards more sophisticated shapes of the parts and higher accuracy of their dimensions. This trend corresponds well with the development of strapdown navigation systems [1], where high precision of parts manufacture is required.

Following the trend of miniaturizing the navigation systems, increasing their performance characteristics and

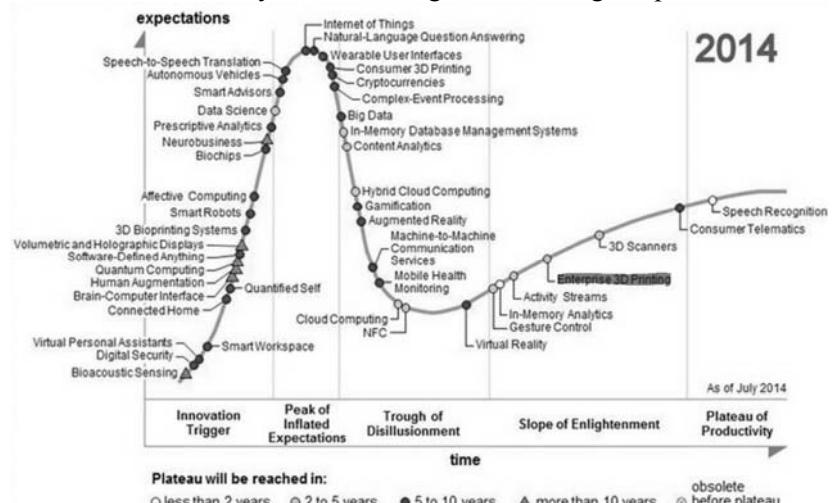


Fig. 1. Gartner hype cycle

application area, the methodology of navigation systems design is continuously developing in the same direction, i.e. complicating the parts and increasing their accuracy. According to the Gartner hype cycle (fig. 1) [2], one of the incoming technologies which could support this trend, especially in case of development time reduction, can be factory 3D-printing.

This paper is aimed to analyze the possibilities for factory metal 3D-printing to support the navigation systems development trend and to be implemented in their manufacturing.

### 1. Problem statement and investigation specimens

To implement the additive technology in navigation system manufacturing, it is essential to investigate the quality and cost of the printed parts and to compare these parameters to similar parameters of the parts manufactured by traditional technologies. For the research, 12 specimens (Fig. 2) manufactured by selective laser melting (additive technology) of steel 316 powder were taken. Setting half of the specimens horizontally and the other half vertically in a building chamber allows examining the anisotropy of the specimens' mechanical properties. Since the research of the additive technology application in navigation systems manufacturing is at the very beginning, there was no possibility to produce the specimens on own printer. For this reason, they were ordered from a third-party company, and technological parameters of printing were not taken into account.

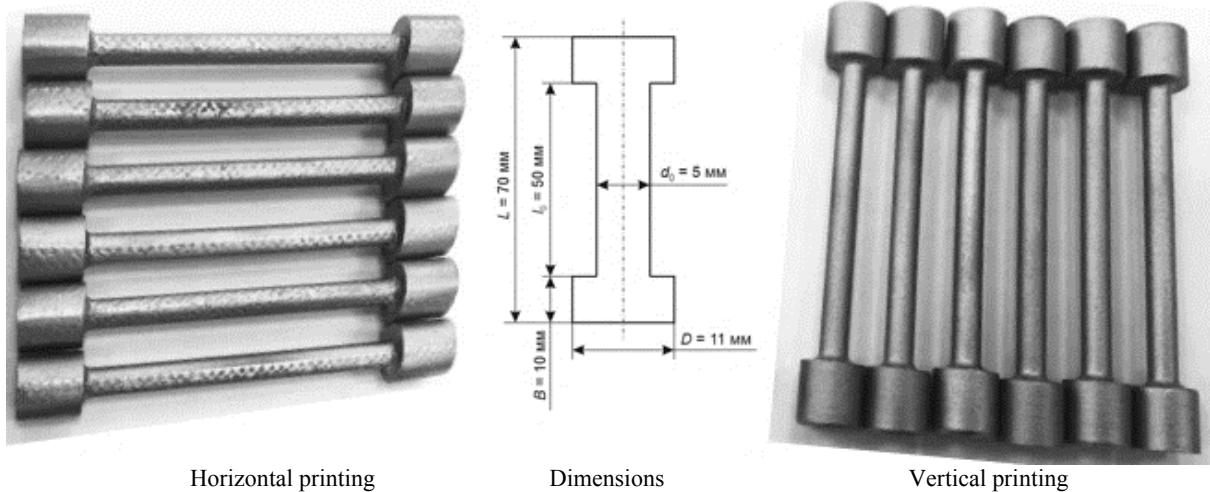


Fig. 2. Specimens of 3D-printed parts

### 2. Tolerances on linear sizes

Each specimen has 5 dimensions to be measured. Deviations of each dimension are presented in table 1 in comparison with the deviations of linear sizes from Russian and international standards [3, 4] which are the same in this case. According to the standards, smaller tolerance classes correspond to more precise parts. The tolerance classes higher than 13 are assigned to non-crucial parts. The tolerance classes between 5 and 12 are related to fittings such as bearings, gear-wheels etc.

Table 1  
Dimensions of specimens

Nominal dimension, mm	Vertical Printing		Horizontal Printing	
	Deviation, mm	Tolerance class	Deviation, mm	Tolerance class
5	-0.03 ... +0.26	14	-0.08 ... +0.03	12
10	+0.00 ... +0.3	14	+0.00 ... +0.15	12
11	-0.08 ... +0.18	13	-0.08 ... -0.01	10
50	-0.05 ... +0.11	11	-0.27 ... -0.2	10
70	+0.47 ... +0.55	10	-0.05 ... +0.03	10

According to the table, the dimension deviations in case of horizontal printing are much smaller. In other words, the accuracy of powder bonding in plane is much better than between the layers. It should be noted that the values of dimension deviations keep at the same level with increasing nominal dimension, which could not be reached with a traditional technology. According to the mentioned standards, this leads to decreasing the tolerance class and, consequently, increasing the entire part precision. Obviously, in case of gimbal navigation systems, almost all geometrical errors in the parts are compensated automatically during gimbal rotation, while in strapdown systems there is no rotation and hence no compensation. At the same time, strapdown navigation systems require much more precise parts than gimbal ones, and the table 1 shows that the additive technology ensures compliance with this requirement.

### 3. Surface roughness and machinability

Photos of surfaces and measured current values of roughness are presented in Fig. 3. The notation “Ra” means an average value per 5 peaks and 5 depressions.

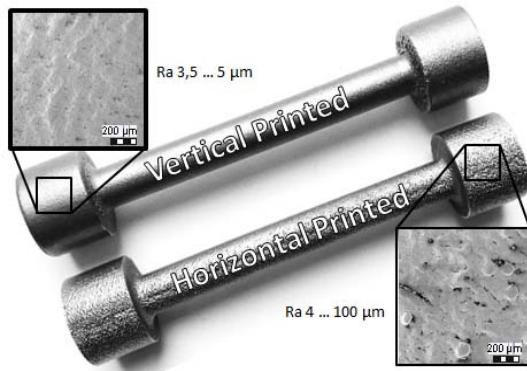


Fig. 3. Raw surfaces

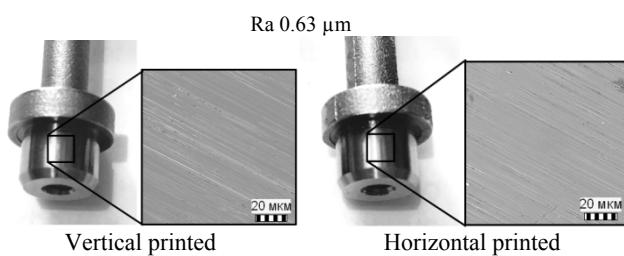


Fig. 4. Machined surfaces

The achieved roughness values are extremely high, especially for horizontally printed specimens. Therefore, there is a serious limitation in manufacturing the metal 3D-printed parts for precise assemblies of navigation systems. In order to check whether this limitation can be overcome, two of the specimens were machined in accordance with the requirements for shape tolerances and roughness of bearing assemblies (Fig. 4). The results showed that the parts had good machinability, all the requirements were met, and the final surfaces of both specimens were smooth and precise. Thus, by merging the additive and traditional technologies, it is possible to obtain quite precise parts and implement them in navigation systems.

### 4. Porosity and strength limits

Porosity is a crucial factor influencing the strength of the parts [5, 6]. One of the methods to determine it is optical metallography. During the investigation, one specimen printed vertically and another one printed horizontally were put into compound. Then they were cut in transverse and longitudinal directions, and their porosity percentage was measured (Fig. 5). All the values are less than 0.8 percent, which means that the porosity of the printed parts is satisfactory and will not affect their strength.

To verify this claim, eight of the specimens were broken up. Four of them were horizontally printed and the other four ones were vertically printed; half of them were heat-treated to relieve melting stress [7, 8]. In addition, two specimens manufactured by traditional technology were broken up in order to get comparative assessment of their strength limits. As a result of the strength tests, ten curves were plotted; two for traditionally manufactured parts, four for raw printed parts, and four (dotted) for heat-treated parts (Fig. 6).

The graphs represent the force applied to specimens versus their strain under this force. The ends of the curves mean the destruction points of the specimens. The linear part in the beginning of the graphs corresponds to linear Hooke's law. Based on these curves, the yield and tensile strength were estimated.

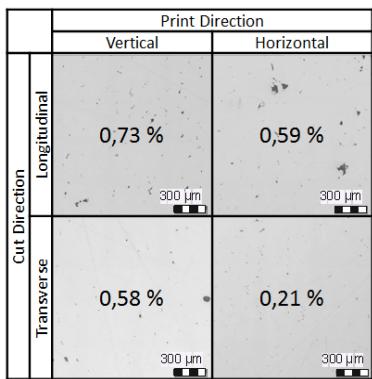


Fig. 5. Porosity of the specimens.

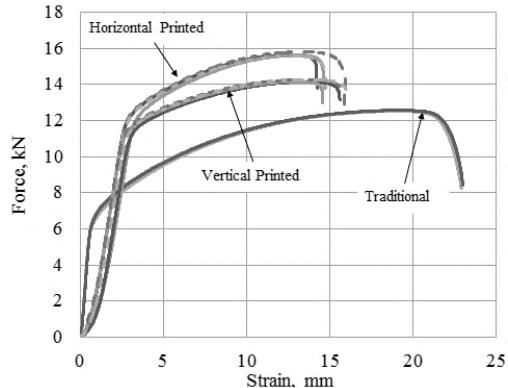


Fig. 6. Strength of the specimens.

The resulting graphs and values suggest the following:

- 1) characteristics of traditionally manufactured parts match the a priori known [9] values, which confirms the tests correctness;
- 2) yield strength of printed parts match well and do not depend on printing direction;
- 3) thermal treatment does not affect the strength limits of the specimens manufactured by additive technology;
- 4) strength limits of the parts manufactured by the additive technology are higher than those of traditionally manufactured ones, which corresponds well to other research [10] and can be explained by vapor condensation nanoparticles forming over the melting zone and by ultrafine-grained structure resulting from selective laser melting [11];
- 5) when traditionally manufactured parts break up, the parts manufactured by the additive technology just lose their elasticity;
- 6) smaller strain of the parts manufactured by the additive technology shows that they are more fragile;
- 7) all curves are quite well-matched, which means that the strength of the printed parts can be controlled by witness specimens.

Summarizing all the above, the strength properties do not impose any restrictions on implementing the additive technology in navigation systems manufacturing.

## 5. Economic efficiency

The costs of traditional manufacturing (CNC-machining) and additive-based manufacturing have been compared (table 2). All costs of the additive technology were calculated and estimated (marked with \*) based on the printer technical parameters and on the weight of the structures under study. The total cost of our specimens is excluded.

The results show that the specimens manufactured by the additive technology are slightly more expensive than the traditional ones. The reason is that they were ordered from a third-party company. If they are manufactured in house, the cost will be considerably lower. The next step was to compare the manufacturing costs of “A Part”. As previously, the estimated cost of printing is lower than that of CNC-machining. It should be noted that pre-production of CNC-machining is quite labor intensive and could be estimated as constant expenses. Therefore, in case of mass production, the total cost of gimbal CNC-manufacturing is much cheaper than printing. At the end of comparison, the manufacturing cost of a small device produced at CSRI Elektropribor was estimated. And again, the additive technology is much more cost efficient as soon as we consider single-unit production. In other words, the maximum economic efficiency of these technologies is achieved with small-scale and piece production [12]. It can be expected that the additive technology implementation in navigation systems manufacturing would reduce the total cost of experimental research and devices.

	Yield Strength	Tensile Strength
Traditional	285,7±7,8	653,2±6,6
Vertical Printed	519±16,5	728±16,2
Horizontal Printed	546,9±13,7	770,6±24,9

Table 2

Cost comparison

Additive Technology		Cost, €	Traditional Technology		
Cost, €			Cost, €		
SPECIMENS					
12*	Material		6,5		
3*	Pre-Production		9		
7*	Manufacturing		470		
570	TOTAL		485,5		
“A PART” (mass production)					
2 700*	Material		280		
72*	Pre-Production		4 300		
900*	Manufacturing		2 700		
3 672*	TOTAL		7 280		
“A DEVICE” (35 parts, 40 kg)					
1850*	Material		50		
85*	Pre-Production		140 000		
40 000*	Manufacturing		94 000		
41 935*	TOTAL		234 500		

## Conclusions

Metal specimens were manufactured by additive technology, and their mechanical properties were investigated. Vertically printed specimens have better roughness, while horizontal printing provides the parts with better tolerances on linear sizes and higher strength limits. Porosity and machinability are quite good for both printing directions. Mechanical properties of the parts manufactured by the additive technology are at the similar level with the traditionally manufactured parts. The additive technology is much more cost-efficient in case of limited production.

Implementing the metal 3D-printing in navigation systems production will reduce the cost of development activities and research works, and allow the quality of resulting parts and devices to be maintained at the level of traditionally manufactured parts.

## Acknowledgments

The authors are grateful to Professor Oleg A. Stepanov for support and funding to the research, and Margarita A. Tit for her assistance with metallographic tests.

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