Using 3D printing technologies for micromechanical sensors production

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Abstract. The paper examines the use of modern technologies of high-temperature multilayer 3D printing (including metal printing) for the production of micromechanical sensors for control and navigation systems. An overview of metal 3D printing technologies is given in this paper. The technologies that can be used for the production of inertial sensors are considered taking into account the requirements for the dimensions of traditional micromechanical devices.

1. Introduction
Developing the technology of manufacturing three-dimensional mechanical structures using technologies and equipment used in microelectronics has opened the way to the creation of microminiature electromechanical systems (MEMS). This new line in the field of instrumentation is called micromechanics.

Developments aimed at creating micromechanical inertial sensors such as micromechanical accelerometers (MMA) and micromechanical gyroscopes (MMG) began in the 1990s in a number of leading laboratories and institutes all over the world. Currently, several large foreign companies (Analog Devices, STMicroelectronics, Honeywell, Bosch, Silicon Sensing, Murata, Systron Donner, etc.) serially produce MMA and MMG. In foreign countries MMG are widely used in the automotive industry, robotics, control systems and navigation systems of various mobile objects (unmanned aerial vehicles, guided missiles etc.).

The attractive qualities of these devices are extremely small dimensions, high reliability and low cost. These qualities lead to their rapid development of MEMS. It is achieved by using group technologies of microelectronics adapted to the manufacture of micromechanical devices. Quality such as the almost complete compatibility of the mechanical part of the devices with the service electronics is also extremely important. The MEMS market has seen significant growth lately.

According to marketing research data, among the MEMS sensors, inertial sensors and systems are of the greatest interest to customers at the moment. According to analytical company Yole, the development of new MEMS sensors is most in demand for the military and aerospace areas, and the annual sales growth is 9% [1]. According to Yole, industrial and commercial applications of MEMS are expected to grow rapidly in the future, with sales growth in these industries reaching 16.5% [1]. This situation is even more typical for the Russian market, since there is no production of high-volume consumer electronic devices.
The most convenient micromechanical sensors and inertial units from well-known world manufacturers, as a rule, do not come to Russia due to the presence of various kinds of restrictions. Over time, the situation escalates, and the number of sanctions only increases. At the moment, there are prerequisites only for further tightening of these restrictions and the introduction of new sanctions. Domestic microelectromechanical sensors and inertial units in many applications do not meet the metrological requirements imposed on them. In this regard, the development of fundamentally new sensors and inertial units built on their basis is becoming extremely urgent, but requires abandoning traditional solutions both in terms of design principles and the use of a new element base.

2. Requirements for 3D printing technologies for the production of micromechanical sensors

The article examines the use of modern technologies of high-temperature multilayer 3D printing, including metal printing, for the production of micromechanical sensors and an inertial unit for control and navigation systems. Previously, such technologies have not yet been widely used to create micromechanical inertial sensing elements.

One of the tasks facing instrumentation today is the creation of precision, highly sensitive micromechanical inertial units, in which the use of processor control and information processing algorithms would be natural due to the essence of the way they function.

In [2], the issues of improving the metrological characteristics of such sensors due to self-oscillating low-frequency operating modes in the pre-resonant region were considered. It has been established that this will expand the possibilities for increasing the efficiency of obtaining information through the technical implementation and for increasing the choice of the operating mode of the sensors. Also, this approach will make it possible to solve the issues of increasing the accuracy characteristics and functionality of advanced control and navigation systems for a wide variety of mobile objects.

The author of this article conducted experiments to create these sensor designs using a 3D printer. The scheme of the implemented structure is shown in figure 1. High (relative to capacitive transducers) power characteristics of the magnetic power transducer [1] allow increasing the mass of the sensing element, which leads to an increase in the sensitivity of the sensor. This allows the use of a relatively high specific weight 3D printed material. Also, the requirements for this material include high strength and low deformability with temperature changes. In addition, it is necessary to take into account the possibility of applying a superconducting film.

![Figure 1. The scheme of the implemented structure.](image-url)
Plastic was a material of inertial mass of created sensor and its elastic suspension elements. However, in terms of its mechanical characteristics, plastic is significantly inferior to silicon widely used today in microelectromechanical sensors. Using metal as a 3D printing material for such a task would be more preferable.

Today 3D printers are able to “grow” a target object layer by layer not only from various polymers and plastic compounds, but also from other working materials: resins, cellulose, glass, ceramics and even metal [3]. However, it is necessary to adapt the existing technologies of multilayer 3D printing to the field of micromechanics. Such adaptation is the researching of the inertial masses production using multilayer 3D printing.

3. Metal 3D printing
It has been a longstanding subject of reducing the cost and improving the quality of products of metal 3D printers [4]. There is a widely recognized trend towards the increasingly widespread use of 3D metal printers, from prototype production to mass production [5]. There is already a factory specializing in the production of components for aircraft jet engines and using in its production only three-dimensional printers that print metal in Italy [6]. 3D printing is used to make bodies and individual engine parts in automotive industry. Automotive companies (Toyota, Mercedes-Benz etc.) are seriously considering using metal 3D printing technology in mass production [6].

During 3D printing, metallic materials undergo complex heat treatment, including melting and rapid solidification. These factors make it difficult to analyze changes in the microstructure of a material and its properties. However, a number of modern scientific works ([7] for example) recognize the possibility of achieving mechanical properties of an object in three-dimensional metal printing comparable to a metal object produced by traditional methods. The reason is that the achievable in 3D printing, relatively high cooling rates reduce the size of the resulting grains and increase the mechanical performance [7].

Metals are widely used in the designs of inertial microelectromechanical sensors existing today, but they are not the main material of the sensitive element. At the current level of development of science, it is difficult to establish which specific material containing the metal most closely matches the previously indicated criteria. This task requires further long-term research, which is widely conducted. Scientific works are constantly appearing on both new methods of metal 3D printing and the choice of printed material. For example, [8].

A number of high-strength alloys, such as based on aluminum, were considered inaccessible for 3D printing. The reason is that elongated or dendritic grains will begin to form in them during the crystallization of the melt. And the melt remaining between them will solidify and decrease in volume upon further cooling. Due to which the cavities and cracks will be formed in the material. In order to avoid the formation of such a structure, the particles of the aluminum alloy powder can be coated with other nanoparticles, for example, zirconium hydride, which, when melted, forms the Al3Zr phase. Many of these nanoparticles on the surface of the powder particles serve as crystallization centers, which ensure the formation of fine equiaxed grains and the absence of cracks and cavities in the final material [9].

Despite the fact that scientific works with the first ideas for the production of MEMS using 3D metal printing began to appear quite a long time ago [10], the creation of individual elements of micromechanical sensors, including the most sensitive element, made of metal right in the 3D printing process still looks extremely promising.

In addition to the fact that metals meet well the previously indicated criteria for choosing a material, such a manufacturing technology will significantly reduce labor costs for production preparation, as well as post-processing, and the total cost of manufacturing a micromechanical sensor (which contains metal elements in the design).

4. Brief overview of metal 3D printing technologies
Metal 3D printers differ from other 3D printing devices in higher weight and most often in larger dimensions. These 3D printers can be conditionally divided into three groups:
• Inkjet printers that work with plastics and low-melting metals such as lead or tin;
• 3D printers based on metal powder with an adhesive. On the basis of such devices, prototypes are printed, which are further subjected to additional firing;
• 3D printers that work on the basis of laser melting technologies. Such details are widely used in industry [3].

Of these three options, the most promising for the manufacture of elements of micromechanical sensors are 3D printers that work on the basis of laser melting technologies. Among such technologies for 3D printing with metal powder are:

• Selective Laser Sintering (SLS) is a 3D method using a material sintered with a laser;
• Selective laser melting (SLM) - metal particles are melted, after which a rigid frame is formed. The production process is carried out in a vacuum chamber filled with inert gases;
• Electron beam melting (EBM). In the electron beam melting process, the metal powder is melted by exposure to electron beams. On the basis of this technology, parts and prototypes for the medical field, aerospace industry, and the automotive industry are being created today [3].

SLS products are superior to conventional metal products in terms of porosity and strength. However, this technology also has a number of disadvantages:

• "dirty" production: the powder is volatile. If it's handled carelessly, then it will rise into the air, clogging the surrounding space and getting into the lungs of a person;
• complexity of the subsequent processing (firing) after printing in a special oven for the final sintering of the powder;
• shrinkage of the manufactured part after firing, sometimes reaching values of 30% (and on average 8-10%) of the original volume, which imposes restrictions on accuracy tolerances and requires subsequent machining to bring to the required quality values [11].

When using SLS, SLM or EBM technologies, the surface can be rough or with visible lamination. The minimum layer thickness is about 0.1–0.15 mm, horizontally. The accuracy is determined by the focusing of the laser beam [12].

The use of STARJET technology allows the use of metals with a melting point of up to 420°C for printing, such as magnesium or zinc alloys (for example, ZAMAK) [13].

One of the relatively new and promising for the manufacture of micromechanical sensors elements is the NanoParticle Jetting technology. This technology is based on the use of metal nanoparticles loaded into special cartridges. Then these cartridges are inserted into the XJet system (the well-known company XJet, which pioneered the use of the technology of three-dimensional printing of objects with liquid metal) and the nanoparticles are passed through spray nozzles, i.e. the material for 3D printing does not need to be touched by hands, which means there is no threat of contamination with toxic substances. Liquid metal passes through the nozzles at a rate of 221 drops per second. The finished metal product is lightly sintered and the supporting structures are removed. It is important that this entire process requires virtually no operator intervention.

[14] describes the use of stereolithography (SLA), fused deposition modeling (FDM), and SLS to create MEMS prototypes. It indicates that when using these technologies today, it is possible to achieve sizes of the order of 50-500 μm. And today there are prospects for achieving sizes of 1-10 μm, which stimulates more active use of 3D printing technologies for a wide range of various micromechanical sensors. An example of a metal object of small size with a production accuracy of more than 1 mm, produced using NanoParticle Jetting technology, is shown in figure 2 [15].
5. Conclusion
3D printing technologies are being used to produce micromechanical sensor prototypes today. The increased use of these technologies for prototyping is considered very promising. The results of the latest developments of new 3D metal printing technologies allow considering their use in the mass production of inertial micromechanical sensors. Particle size and ultra-thin material layers enable the transfer of fine details and thin-walled products. By removing the supporting materials, in this case, you can easily create products of high complexity structure, the smallest details and a perfectly flat surface. Moreover, it is relevant for self-oscillating micromechanical sensors due to the possibility of implementing a large inertial mass and large dimensions of suspension elements in their design.

Figure 2. The example of a metal object produced using NanoParticle Jetting technology.

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