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Factory of the Future – new solution and new quality in scientific instrumentation

Dmitry Novikov^{1,2,*}, **Alexander Veretennikov**^{1,3}, **Alexey Borodin**^{1,4} and **Alexander Snedkov**¹

¹ MIREA Russian Technological University Vernadsky Ave., 78, Moscow, 119454, Russia

² Bauman Moscow State Technical University, 2-ya Baumanskaya st., 5, Moscow, 105005, Russia

³ Engineering Center EZAN, Academician Semenov Ave., 9, Chernogolovka, 142432, Russia

⁴ Laboratory of Controlled Crystal Growth, ISSP RAS, Academician Ossipyan str., 2, Chernogolovka, 142432, Russia

* Email: zerooo@list.ru

Abstract. Scientific instrument making is one of the key drivers for the economy of a highly developed country. R&D and manufacturing of scientific devices and equipment in the Russian Federation have been facing a lot of different obstacles during recent decades. The weak link is the transition of the results of fundamental and applied research into prototypes of products, as well as the subsequent organization of mass production. In particular, the problem is the lack of seamless knowledge transfer processes from researchers to developers, as well as the extremely high price of manufacturing samples of scientific instruments and equipment. In this paper we consider the state of art concept of Future plant implementation for scientific instrument making. We also demonstrate an example of successful using of digital technologies in high-tech equipment development project.

1. Introduction

Expansion of R&D works carried out, in particular, in the structure of the Ministry of Science and Higher Education of the Russian Federation, reveals the urgency of creating technological instruments, ensuring rapid transfer of research results to the stage of practical application. Scientific devices and technologies being developed should be implemented in organizations operating in the real economy. Scientific instrument making is an area in which the introduction of the above effective instruments is extremely required in connection with the Decree of the President of the Russian Federation [1] in the part of solving the following tasks:

- renewing not less than 50 percent of the instrument base of leading organizations performing scientific research and development;
- creation of world-class scientific centers, including a network of international mathematical centers and centers for genomic research;



- creation of at least 15 world-class scientific and educational centers on the basis of integration of universities and scientific organizations and their cooperation with organizations working in the real sector of the economy;

2. Problem

One of the problems of the development of domestic scientific instrumentation is the lack of enterprises capable of promptly solving the tasks of developing and producing scientific instruments, equipment and their components – both unique ones that have limited applications (i.e. for scientific research), and those that are planned to replicate for a wide range of customers.

Nowadays the need for a new type of enterprise, the Factory of the Future, which is able to quickly respond to an individual (customized) request and present the product to the customer at a price comparable to serial production, has become evident.

An important feature of such an enterprise should be the ability to work with customers at different levels of technology readiness (TRL), including the lowest TRL level of fundamental research.

The concept of Factory of the Future (FoF) includes a set of technological solutions (integrated technological chains) that ensure the design and manufacture of globally competitive products of the new generation in the shortest possible time [2]. The FoF includes the concept of Digital Factory [3], which uses computer engineering technologies, primarily digital modeling and design of both the products themselves and production processes throughout the life cycle of the product (PLM) [4]. The second FoF key element is the Smart Factory [5] – a global automated system for overall technological and production processes, which allows quick re-equipment of production facilities with no human intervention. The third FoF key element is the Virtual Factory [6], which is, in fact, a distributed network of "digital" and "smart" factories linked together on the basis of technologies for managing global supply chains and production assets [7].

R&D commercialization in the field of scientific instrumentation in modern environment requires implementation of the PLM concept. Appropriate standards have already been released in Russia. So GOST R 56862-2016 [8] establishes the basic terms and definitions of a life cycle management system, while others are standard in this series, for example, GOST R 56864-2016 [9] and GOST R 56864-2016 [10] impose specific requirements on the features of the work.

On the one hand, a new product should be introduced to the market as soon as possible, and on the other hand, the new product must meet the highest requirements of potential customers, already at the stage of the first test samples. The traditional R&D stages [11] including prototypes, pilots, long-term tests (including resource tests), numerous adjustments of design and technological documentation become a time-limiting and very resource-intensive task. As a result, a scientific device or equipment enters the market with a great delay, or does not go out at all.

In addition, the most important task in the creation of namely complicated high-tech products is quality management. In the field of instrument-making, where products are often produced in small batches or even in a single copy, quality should mean the conformity of the product to the customized requirements of the customer. It is necessary to focus on the quality of management of all business processes, paying particular attention to product development processes. At first glance, all decisions in the field of quality management have long been used by enterprises. There are many ERP systems designed to facilitate enterprise management. However, the introduction of the principles of FoF mechanisms allows the integration of ERP systems with systems for the development of high technology products (CAD/CAE), which in turn should be associated with production support systems – MES, PDM, CAPP, MRP, and so on. Such a combination will provide support for managing the entire life cycle and, accordingly, its quality, the traceability of all changes in documentation at every stage of production will be ensured: from the development of design documentation to programs for CNC machines; from purchased materials to serial numbers of products where they were used. Feedback is provided to restore the entire sequence of actions and their initiators.

The solution to the above problem is, among other things, the use of modern instruments for the development and production of high technology equipment, namely, the use of digital technologies: virtual modeling, developing of design and technological documentation, virtual testing, etc.

3. Solutions and examples

As a successful example of the implementation of digital approaches in the creation of innovative high technology products, we consider the process of developing and manufacturing automated equipment for oxide single crystal growing.

The developer and manufacturer of the equipment is the Federal State Unitary Enterprise Experimental Enterprise for Scientific Engineering with the Special Design Department of the Russian Academy of Sciences (EZAN). One of the main activities of EZAN is the development and manufacturing of scientific instruments and equipment in cooperation with research institutes. It is important to emphasize that the EZAN already successfully uses the basic elements of digital production. The enterprise has developed and implemented its own financial management and production system – ERP “Kedr”, which includes modules PDM, CAPP, APS/MES, MRO, CRM and FI. In the enterprise management system, CAD and PLM of third-party developers as well as supply and accounting management systems are integrated. Financial planning of the enterprise is provided taking into account actually concluded and predicted contracts. A digital production model is built taking into account the actual capacities of the machining centers and production cycles. CAD/CAM/CAE modules are based on CAD “Creo” and “COMPAS-3D” software [12].

The organization that carries out fundamental and applied research in this field is the Institute of Solid State Physics of the Russian Academy of Sciences (ISSP RAS). The main issue in the development of equipment for growing crystals is the design of the thermal unit and the selection of its operating modes to ensure high quality of grown crystals and a high yield of suitable growth processes [13], which determines the economic efficiency of the equipment as a whole [14]. Thus, the stage following fundamental and applied research should be the development of a multiparametric virtual model (Digital MockUp – DMU) of the key elements of the equipment.

Numerical simulation of the effect of structural features of a thermal unit on the temperature distribution and the magnitude of thermal stresses in a crystal is an effective process and equipment optimization tool [15] provided that the main interrelated physical phenomena accompanying the growing process are considered [16]. In the present work we consider the problems of induction heating [17], heat transfer in solids, liquid and gas [18], radiative heat transfer [19], melt and gas dynamics, thermo elasticity. The problems were solved numerically by the finite element method, using COMSOL Multiphysics[®] software.

The pronounced axial symmetry of the cylindrical chamber of the installation, the inductor and the main elements of the thermal unit allows using the two-dimensional axisymmetric model. Figures 1-2 presents thermal unit heated by induction for shaped sapphire crystals, its geometric model, and the subdivision of the computational domain into a grid of finite elements. The thermal unit for growing crystals of complex shape by dynamic shaping technique is practically identical except for the geometry of the holes in the upper part, which allows horizontal movement of the crystal.

The thermal unit is installed in the water-cooled chamber (1), coaxially passes through the inductor (2) and includes the graphite cylindrical heater (induction current concentrator) (3), the thermal insulation (4), the die (5), the radiation screens (6), the crucible (7) mounted on the support (11) connected to the water-cooled rod (10), the melt (8), the grown crystal (9), the platform (12). The growing process takes place in an argon atmosphere.

The initial step is to determine the intensity of the electromagnetic field created by the induction coil, ohmic losses, and heat release of the elements of the thermal unit. At the second step, the problems of heat transfer, melt and gas dynamics are jointly solved, and the temperature distribution, the velocity fields of the liquid and gas phases, the position and shape of the crystallization front are found. Finally, the field of temperature stresses in the crystal is calculated.

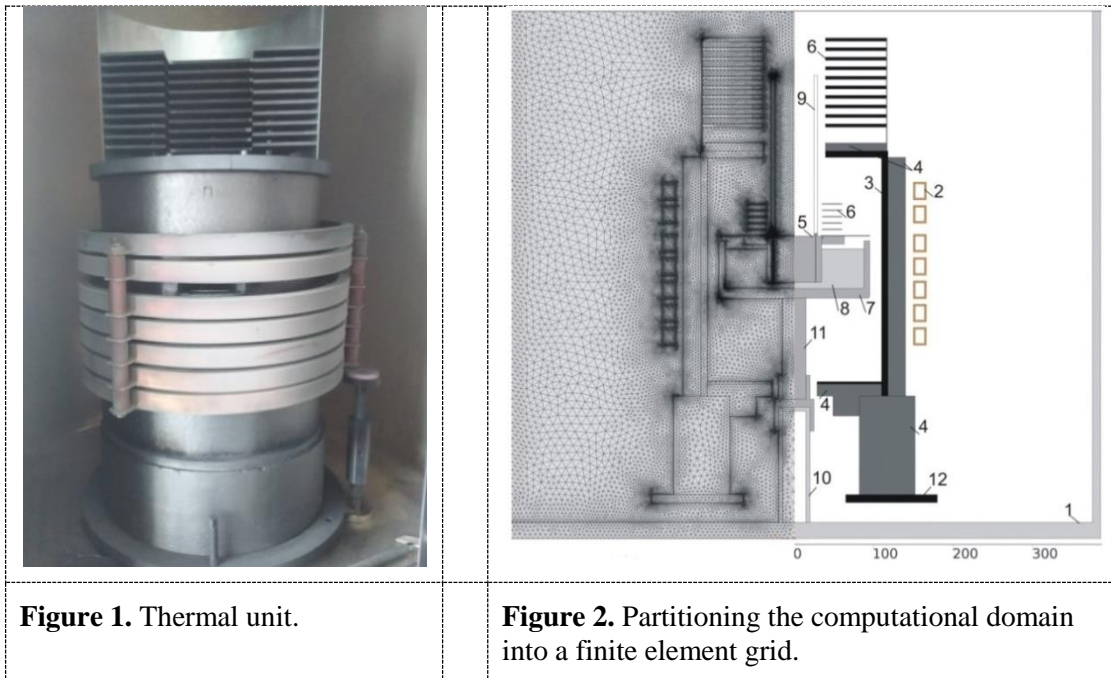


Figure 1. Thermal unit.

Figure 2. Partitioning the computational domain into a finite element grid.

The values of the physical coefficients, such as the thermal conductivity of the materials, the absorption coefficient of sapphire were set taking into account their temperature dependence. The coefficients of dynamic viscosity, thermal conductivity and heat capacity of the melt and gas were assumed constant, corresponding to the main temperature range. The dependence of the melt density on temperature was assumed to be linear [20], and the density of gas was calculated according to the Clapeyron equation. The coefficient of temperature expansion of sapphire was taken constant and equal to $6E^{-6}K^{-1}$. Numerical simulation was carried out for the typical growth process of the tube. The temperatures of the walls of the water-cooled crystallization chamber, the lower rod and inductor (positions 1, 10, 2, Figure 2) we set equal to the temperature of the incoming cooling water ($20^{\circ}C$). The frequency of the source of induction heating $f = 11$ kHz corresponded to its real value of the transistor generator.

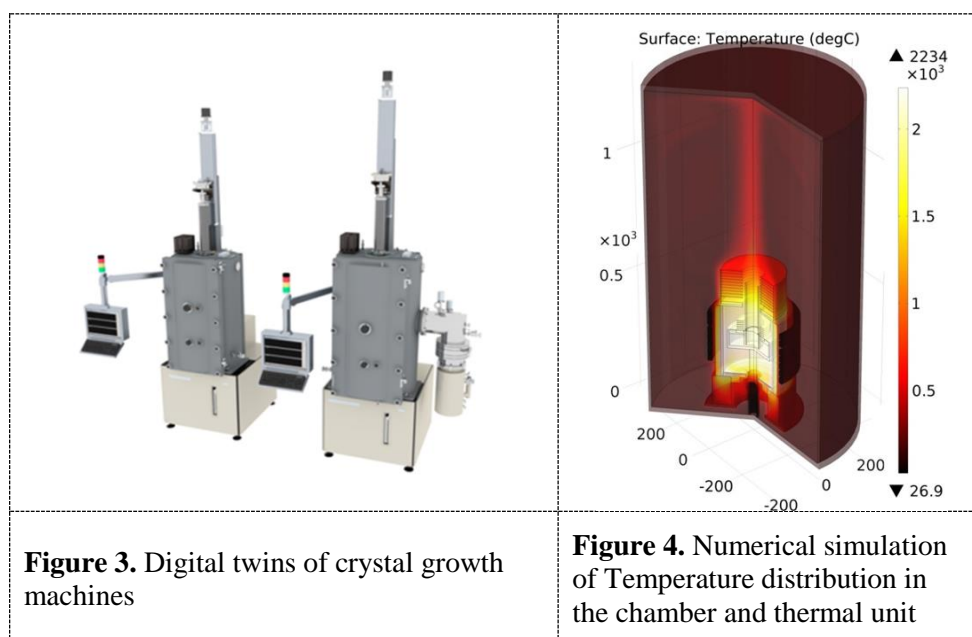
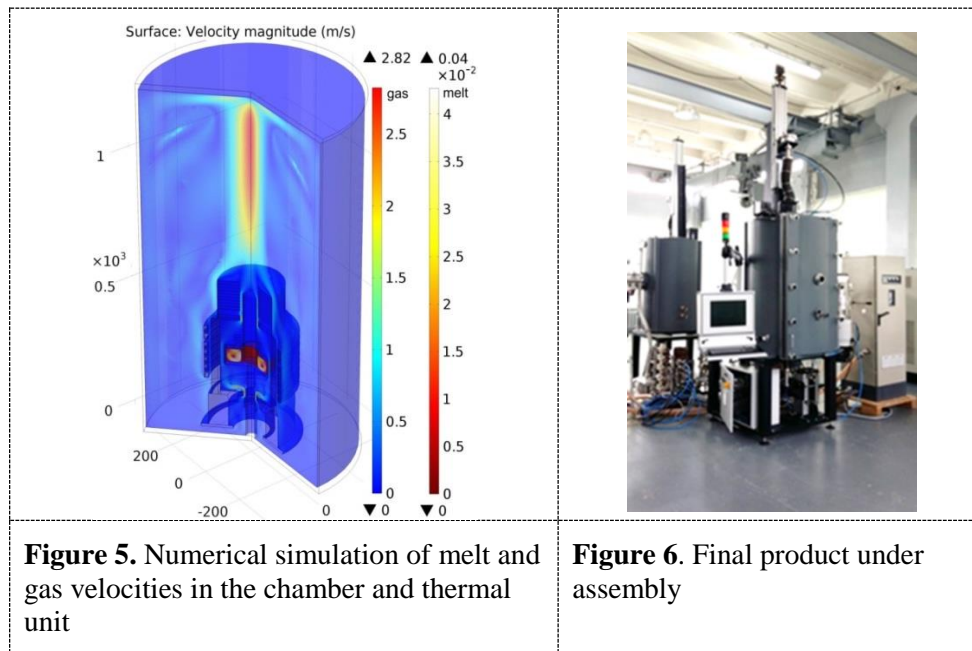


Figure 3. Digital twins of crystal growth machines

Figure 4. Numerical simulation of Temperature distribution in the chamber and thermal unit



As the result the virtual thermal unit (so-called the «heart of the equipment») has been developed and its influence on the crystal growth process (temperature and stresses distribution in crystal) as well as interaction with the whole equipment was studied under the number of design parameters and optimal engineering solutions were found. Figures 3, 4, 5, and 6 demonstrate the chain of product development starting with digital twin (Figure 3), having its virtual testing (Figures 4, 5), and ending with the real product (Figure 6).

It is obvious, the introduction of the concepts of Digital Factories (and more globally, the Factories of the Future) should provide a significant increase in the efficiency of R&D results transfer to the real economy, as well as ensure the implementation of the concept of supporting the full life cycle of the product (PLM).

To implement the project Factory of the Future for scientific instrumentation, it is necessary to solve the following problems.

1. Creation of a distributed information environment for the operational interaction of the enterprise with the customer, co-executors, suppliers and experts;

2. Providing work with customers, who are at any level of technology readiness (TRL), including basic and applied research:

- primary interaction with the customer using digital technologies;
- prompt reaction and informing the customer about the principal possibility of development and manufacturing;
- use of a database of similar developments of the enterprise, consisting of both standard and unique solutions;
- prompt delivery of preliminary 3D models of products to the customer.

3. Involvement of the customer in the process of development of design documentation with the possibility of its multiple corrections when changing its requirements:

- a customer becomes a "virtual engineer" and acts in constant contact with the developers;
- a customer has access to the developed documentation with the possibility of making proposals on adjusting his requirements at any stage.

4. Ensuring the operational technological preparation of production and the readiness of production for solving the problems of manufacturing scientific devices and equipment using advanced production technologies:

- application of modern elements of "digital" and "smart" factory concepts;

- modernization of production and its equipping with high-performance machining centers;
- staff training.

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