IMPLEMENTAÇÃO DA PROTOTIPAGEM RÁPIDA NA RESOLUÇÃO DE PROBLEMAS APLICADOS NA PRODUÇÃO

INTRODUCTION OF RAPID PROTOTYPING IN SOLVING APPLIED PROBLEMS IN PRODUCTION

ВНЕДРЕНИЕ БЫСТРОГО ПРОТОТИПИРОВАНИЯ ПРИ РЕШЕНИИ ПРИКЛАДНЫХ ЗАДАЧ НА ПРОИЗВОДСТВЕ

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RESUMO

Todas as linhas e máquinas transportadoras devem funcionar sem problemas durante a produção para lançamento dos produtos oportuno. Existem peças e componentes, cuja falha leva à falha de toda a transportadora. É o tempo de entrega e as perdas financeiras devido ao tempo de inatividade do equipamento que tornam relevante o problema de reprodução rápida da peça para substituir a original. Neste artigo, consideramos o processo de criação de uma peça de teste usando a tecnologia de fusão seletiva a laser (SLS). Nesse caso, a eficiência econômica da produção de produtos depende diretamente da solução eficaz e correta dos problemas de preparação tecnológica da produção aditiva. A amostra impressa foi testada em contato direto com o meio aquoso por 500 horas. Os testes de fadiga foram realizados utilizando 40% de pó primário e 60% de pó secundário. Para a avaliação quantitativa das propriedades do material com uma dada geometria, foi realizada uma série de testes de ruptura dos produtos da peça. Para identificar a melhor proporção de resistência, elasticidade e custo de fabricação, nos testes foram apresentadas as amostras com diferentes porcentagens de pó. Observou-se que o custo de fabricação de peças, ferramentas e acessórios de reposição usando a impressão 3D depende de muitos fatores. Os principais fatores de influência foram a geometria dos produtos, que determina seu volume, bem como a densidade de sua disposição na câmara. A experiência acumulada e a análise dos critérios nos permitiram oferecer várias opções de layout que podem levar ao máximo efeito econômico.

Palavras-chave: *engenharia reversa, retentor, digitalização 3D, layout automático.*

ABSTRACT

All conveyor lines and machines should work smoothly in order to ensure a well-timed production during production. There are parts and nodes, the failure of which leads to the failure of the entire conveyor. It is the delivery time and financial losses due to equipment downtime that make the problem of quick reproduction of the relevant part to replace the original one. In this work, the process of creating a test piece using selective laser fusion (SLS) technology was considered. In this case, the economic efficiency of the fabrication of products depends directly on the effective and correct solution to the problems of technological preparation of additive production. The printed model was tested in direct contact with water for 500 hours. Fatigue tests were performed using 40% primary and 60% secondary powder ratios. To quantify the properties of the material for given geometry, a series of tensile testing of products was carried out. To identify the best ratio of strength, elasticity, and manufacturing cost for testing, samples were offered with different percentages of powder. It was noted that the cost of manufacturing spare parts, tools, and accessories (SPA) using 3D printing depends on many

factors. The product geometry determines their volume, and the density of their arrangement in the chamber was recognized as a crucial impact factor. The accumulated experience and analysis of the criteria allowed us to offer several layout options that can lead to a maximum economic effect.

Keywords: *reverse engineering, fixator, 3D scanning, automatic layout.*

АННОТАЦИЯ

Все конвейерные линии и станки должны работать бесперебойно во время производства для обеспечения своевременного выпуска продукции. Существуют детали и узлы, поломка которых приводит к выходу из строя всего конвейера. Именно сроки поставки и финансовые потери из-за простоя оборудования делают актуальным вопрос быстрого воспроизводства детали для замены оригинальной. В данной работе рассмотрен процесс создания тестовой заготовки по технологии выборочного лазерного сплавления (SLS). В данном случае экономическая эффективность производства изделий зависит напрямую от эффективного и корректного решения задач технологической подготовки аддитивного производства. Напечатанный образец тестировался в непосредственном контакте с водной средой в течении 500 часов. Испытания на усталость проводились с использованием 40% первичного и 60% вторичного соотношения порошка. Для количественной оценки свойств материала при заданной геометрии был проведен ряд испытаний изделий-заготовок на разрыв. Для выявления наилучшего соотношения по прочности, эластичности и стоимости изготовления на испытания были представлены образцы с разным процентным соотношением порошка. Было отмечено, что стоимость изготовления запасных частей, инструментов и принадлежностей (ЗИП) с помощью 3D-печати зависит от множества факторов. Ключевыми факторами влияния были признаны геометрия изделий, определяющая их объем, а также плотность компоновки их в камере. Нарботанный опыт и анализ критериев позволил предложить несколько вариантов компоновок, которые способны привести к максимальному экономическому эффекту.

Ключевые слова: *реверс-инжиниринг, фиксатор, 3D сканирование, автоматическая компоновка.*

1. INTRODUCTION

Many works have been devoted to the development and modeling of complex composite structures from anisotropic materials (Babaytsev *et al.*, 2017; Koshoridze *et al.*, 2017; Babaytsev, and Zotov, 2019; Babaytsev *et al.*, 2019). Mainly, one of the options for obtaining such structures is 3D printing (Nazarov, 2011; Boytsov *et al.*, 2011; Atzeni and Salmi, 2012; Mellor *et al.*, 2014; Bepalov *et al.*, 2019; Kuzovkin and Suvorov, 2014; Piller *et al.*, 2015; Anamova *et al.*, 2016; Ripetskiy *et al.*, 2016; Babaytsev *et al.*, 2017; Rabinskiy *et al.*, 2017; Ripetskiy *et al.*, 2018; Kuprikov *et al.*, 2019). The area of use of such products is too vast. For example, to ensure the timely manufacture of products, the operation of all conveyor lines and machines should run smoothly. Failure per under such conditions may not be dangerous, provided that spare parts, tools, and accessories are available (SPA) (Bhutani *et al.*, 2017; Böckin and Tillman, 2019; Kolotyryn *et al.*, 2019; Westerweel *et al.*, 2019; Pellens *et al.*, 2020). However, there are parts and components, the failure of which leads to failure of the entire conveyor (Boboc *et al.*, 2019; Zhang, 2019). In the conditions of reality of Russian industrial enterprises to supply spare parts (including ones

of foreign manufacture) is difficult and to predict when the break occurs is not always possible. Therefore, with a slight breakdown, the entire production line can stop (Zhang and Chang, 2011; Yumashev *et al.*, 2019; Bulavin *et al.*, 2018).

Using the example of individual elements of the conveyor, it can be considered the reverse engineering cycle, timing of reproduction, and economic effect compared with the original part. The fixator (Figure 1) is a part of the conveyor for moving workpieces. This part is a knowingly weak link of the machine and most frequently fails. At the same time, it is impossible to predict how long the original part will last. The reason for this includes several factors:

1. The part works in constant contact with workpieces, due to which there is wear at the points of contact.
2. The occurrence of a defective workpiece can ruin the part and damage it.
3. Failure of automatic workpiece feed mode and also disables the part.
4. This part is knowingly weak link to prevent a chain reaction of breakdowns on the conveyor – when the fixator fails, and the workpieces are not transferred further along the

line.

The cost of the original part “fixator” is over 800 units, and the delivery time takes about 1.5 weeks. It is delivery times and financial losses due to equipment downtime that make the issue of quick reproduction of parts relevant for replacing the original ones (Song and Zhang, 2016; Alekseev *et al.*, 2019; Sobczak-Kupiec *et al.*, 2012; Sobczak-Kupiec *et al.*, 2018). The cycle, including 3D scanning, 3D printing using SLS technology, processing, and delivery, takes from 2 to 4 days (Georgios Tsoutsos *et al.*, 2017; Kim, 2019; Tashi *et al.*, 2019; Skvortsov *et al.*, 2012). Depending on the volume and arrangement of the chamber parts and the proportions of the powder used, the benefit can be 50 to 60%. Going through reverse engineering, revision, and printing cycle is becoming preferable for enterprises than waiting for the original spare part (Revilla-León *et al.*, 2018; Sevryukova *et al.*, 2012; Revilla-León *et al.*, 2019; Koltunov *et al.*, 2018; Revilla-León *et al.*, 2020).

2. MATERIALS AND METHODS

In this article, the process of creating a test piece using selective laser fusion (SLS) technology was considered. In this case, the economic efficiency of manufacturing the products depends directly on the effective and correct solution to the problems of technological preparation of additive production. The most powerful influence on the result is exerted by the task of the technical layout of products in the construction chamber — the search for a layout solution.

To obtain high-quality electronic models for real products, three-dimensional scanning equipment was used – the FARO Arm EDGE coordinate measurement machine (CMM) and the Kreon ZEPHYR KZ25 laser nozzle. The working area of the CMM is 1800 mm, which is sufficient to obtain electronic models of any spare parts and elements of the conveyor belt line. The Kreon ZEPHYR KZ25 non-contact laser scanner has the technical characteristics presented in Table 1. The use of such mobile CMMs and easily removable nozzles (non-contact laser scanners) calls for their use in close proximity to the production site, which helps to quickly obtain the desired product. The electronic models obtained from the measurement results were put into production.

The arrangement of products is made according to some limiting criteria (Ripetskiy *et al.*, 2016). The experience obtained during the work

with the installation of selective laser sintering EOSINT P 395, allowed to highlight the most important of them:

- the indent from walls of the build chamber to the nearest part should be at least 15 mm;
- the distance between any two points on the surface of two different parts should not exceed 6 mm;
- in order to maintain the homogeneous structure and, as a result, the same strength characteristics, all products, in the beginning, should be oriented identically with respect to the growing direction (vectors perpendicular to the layers of future products should be collinear).

The key parameters that affect cost of the product at the stage of assembly are:

- layout height;
- layout density, determined from the volume of parts placed at the beginning of a given height;
- time spent on choosing the optimal layout solution;

It is important to note that an attempt to increase density of layout and neglect the criteria reduces the reliability of the launch and can lead to spoilage of products, and even to failure of the installation of SLS-printing (Willmann, 2019). Figure 2 displays a horizontal arrangement of the components in manual mode, this layout has height of construction 32 mm and can accommodate 18 parts. The horizontal arrangement allows us to use less material along the height of chamber, but the percentage of unused material is quite high. To calculate the cost of printing, it is should be considered the following indicators:

- assembly height – 26.63 mm;
- placement density – 14.22%;
- use of platform volume – 0.61%;
- volume of parts – 437.834 cm³;
- number of parts – 18 pcs.

To achieve the optimal value, it is necessary to increase the number of parts, while reducing the density of placement, taking into account the layout criteria listed above. Subject to the above parameters, taking into account the manual arrangement of parts in chamber, the probability of operator error is high, while the time cost is significantly increased. The best solution

would be to use automatic layout. Figure 3 illustrates realization of automatic layout of fixators in vertical arrangement. In a vertical arrangement, more material is used along height of the chamber, while the number of parts has increased by more than 3 times.

Key indicators for layout variant No. 2 will be as follows:

- assembly height – 90.05 mm;
- density of placement – 16.41%;
- use of platform volume – 2.31%;
- volume of parts – 1605.389 cm³;
- number of parts – 66 pcs.

Another important technological limitation is the requirements of SLS-print to the part geometry and resolution of EOSINT P 395. One example is the impossibility of accurately producing functional holes whose axes are perpendicular to the growing direction. Thus, for example, the product fixing the conveyor belt (Figure 4) has a simple geometry in terms of topology, but it takes up quite a lot of space in the construction chamber when placed taking into account the above technological limitations.

Subject to all technological requirements, the density remains small, and the number of parts does not exceed 23 pieces. Figure 5 shows a possible dense arrangement for the parts.

Key indicators for layout of variant No. 3 will be as follows:

- assembly height – 41.27 mm;
- placement density – 10.74%;
- use of platform volume – 0.71%;
- volume of parts – 512.401 cm³;
- number of parts – 23 pcs.

Further analysis will demonstrate that this arrangement will not be cost-effective for the introduction of printed fixative products as spare parts for conveyor belts.

The products were made of PA2200 polyamide powder as the most affordable for the selected technology (SLS), as well as having excellent strength and chemical resistance specifications. Technical specifications of this powder are presented in Table 2.

3. RESULTS AND DISCUSSION:

SLS technology allows using unprocessed powder material repeatedly. The percentage of

primary and secondary material affects both product properties and pricing. Thus, for example, the cost of a holder when printing exclusively on secondary powder is 100 units. This increases the flexibility of the product, which affects the operation quality. In order to find the optimal proportion in terms of cost in this case, it is necessary to make products with different proportions of the primary and secondary powder in various operating modes. According to the results, changes to the material's geometry (e.g. increasing the wall thickness with a ratio of "0/100") or increasing the amount of primary material to the detriment of the product's cost are needed.

Since the printed part has a porous structure, it is necessary to take into account the hygroscopicity of the product and its effect on operational characteristics. Figure 6 demonstrates the change in mass compared to the original part before and after testing. The weight of the printed holder before the test was 23.23 g. The printed sample was tested in direct contact with the aqueous medium for 500 hours, while the weight increased to 24.08 g. for sample No. 1 and to 24.31 gr. for sample No. 2. The clearance between the clamps has increased from 0 to 1 mm. Fatigue tests were performed using 40% primary and 60% secondary powder ratios. The functional characteristics of the holder remained in the normal range (Mustafin, 2006; Mustafin and Volkov, 1984).

At the moment, the samples with a different material ratio undergo strength and fatigue tests (Table 3). To quantify the properties of the material for the given geometry, a series of tensile testing of blanks were performed. To identify the best ratio of strength, elasticity, and manufacturing cost, samples with different percentages of powder were offered for testing. So, samples 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7 have a ratio of 40 % of the primary powder and 60% of the secondary, while samples 1.6 and 1.7 were already tested under production conditions for 2.5 months of continuous operation (Mellor *et al.*, 2014). Samples 1.8 and 1.9 were made entirely of secondary powder, and in the graphs below, it can be seen that these samples are the most elastic. Tensile tests were performed at a speed of 25 mm/min. Figure 7 presents graphs demonstrating the maximum load of the test samples.

The graph shows that the samples, printed with the use of 3D printing, can stand high maximal loads. Products 9 and 10 printed with a 100% ratio of secondary powder have greater elasticity and did not collapse during testing. Static tests were

also carried out at the same time, the task of which was to determine the boundary conditions, after which the sample would lose its elasticity and cease to take its original shape. Table 4 shows the result of static tests of the holding part for 3 months. The highlighted test holder is marked by red, the blue stands for the original holder (Figure 8) (Anamova *et al.*, 2016; Umbetov *et al.*, 2016a; Umbetov *et al.*, 2016b; Rabinskiy *et al.*, 2017). Comparison of the geometries of the original and used holders showed an increase in the gap between the arcs by 5 mm; in this state, the holder is still able to fulfill its main function of holding the workpieces, but such a part must be replaced (Rabinskiy *et al.*, 2017). Problems prototyping are regarded in (Nazarov, 2011; Kalinsky *et al.*, 2019; Boytsov *et al.*, 2011; Atzeni and Salmi, 2012; Kuzovkin and Suvorov, 2014; Piller *et al.*, 2015).

4. CONCLUSIONS:

This work mentions that the cost of manufacturing spare parts using 3D printing depends on many factors. The geometry of the products, which determines their volume, as well as density of their arrangement in the chamber, were recognized as key factors of influence. The same factors become criteria for the economic efficiency of using SLS technology to solve applied production problems.

Several technological parameters and criteria were analyzed that limit the technical engineer in creating effective layouts. The accumulated experience and analysis of the criteria allowed us to suggest several layout options that can lead to a maximum economic effect. Another critical factor is the improvement in the time of delivery of the finished product to the production line. Analysis of specific production line (Nizhnelomovsky enterprise of the United Penza Plant) demonstrated that timely production of spare parts by 3D printing could reduce delivery time by an average of 2 days.

Therefore, the use of SLS printing for the production of individual elements of the conveyor line can reduce delivery times by an average of 2 times, and for individual products - by 2.5-3 times. The cost of a single product decreases by an average of 37.5 %, and for individual products, it is 1/3 of the cost of the original spare part. This effect was proved on example of specific products and can partially be transferred to other applications for quickly creating spare parts in production conditions. The issue of expanded use of SLS printing, as well as other rapid prototyping tools, is part of the task of further research on the

subject.

In addition to the above-mentioned positive effects of the introduction of 3D printing, it is necessary to take into account the series and uniqueness of products, and it is important to understand at which stage it can be switched to other production technologies. Further tasks in this direction are to determine the criteria and requirements for the geometry of products, as well as to create a mathematical apparatus that could let us confidently determine the production technology of specific products to achieve the maximum economic effect. Presently, work in this direction is also proceeding.

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Table 1. Kreon ZEPHYR KZ25 Laser Scanner Specifications

Data collection speed	34 fps, up to 30,000 dots/s
Number of laser lines per second	60
Accuracy, mm	±0.015
Sensor resolution	0.005
Linear resolution	0.03
Laser type	Signal modulation diode
Laser class	II
Wave length, nm	675
Maximum power, mW	3.7

Table 2. Mechanical properties of polyamide PA2200

Mechanical properties	Value	Unit	Test Standart
Izod Impact notched (23°C)	4.4	kJ/m ²	ISO 180/1A
Shore D hardness (15s)	75	-	ISO 868
Tensile Modulus (X Direction)	1650	MPa	ISO 527-1/-2
Tensile Modulus (Y Direction)	1650	MPa	ISO 527-1/-2
Tensile Modulus (Z Direction)	1650	MPa	ISO 527-1/-2
Tensile Strength (X Direction)	48	MPa	ISO 527-1/-2
Tensile Strength (Y Direction)	48	MPa	ISO 527-1/-2
Tensile Strength (Z Direction)	42	MPa	ISO 527-1/-2
Strain at break (X Direction)	18	%	ISO 527-1/-2
Strain at break (Y Direction)	18	%	ISO 527-1/-2
Strain at break (Z Direction)	4	%	ISO 527-1/-2
Charpy impact strength (+23°C, X Direction)	53	kJ/m ²	ISO 179/1eU
Charpy notched impact strength (+23°C, X Direction)	4.8	kJ/m ²	ISO 179/1eA
Flexural Modulus (23°C, X Direction)	1500	MPa	ISO 178
Melting temperature (20°C/min)	176	°C	ISO 11357-1/-3
Vicat softening temperature (50°C/h 50N)	163	°C	ISO 306
Density (lasersintered)	930	kg/m ³	EOS GmbH Method

Table 3. The economic effect from the introduction of 3D printing for the production of spare parts

Product type	Delivery time		Cost, USD		
	Original	3 D printing	Original	3 D printing 40/60	3 D printing 0/100
Fixator type 1	from 2 days	3-4 days	from \$ 12.3	\$ 3.3	\$ 1.5
Fixator type 2	from 2 days	3-4 days	from \$ 13.9	\$ 3.5	\$ 1.7
Fixator Parametric Model	from 2 days	3-4 days	n / a	\$ 3.5	\$ 1.5
Holder bracket for blanks	1.5 weeks	3-4 days	from \$ 6.2	\$ 4.5	n / a

Table 4. *The test results*

Sample label	Maximum load [kN]	Ultimate strain [%]	Note
1.0	0.2	34.433	Test speed 25 mm / min. Original
1.1	0.36	55.37	Test speed 25 mm / min. Polyamide.
1.2	0.35	54.62	Test speed 25 mm / min. Polyamide.
1.3	0.37	57.599	Test speed 25 mm / min. Polyamide.
1.4	0.29	53.741	Test speed 25 mm / min. Polyamide.
1.5	0.34	53.599	Test speed 25 mm / min. Polyamide.
1.6	0.31	55.391	Test speed 25 mm / min. Polyamide (was in operation).
1.7	0.33	54.745	Test speed 25 mm / min. Polyamide (was in operation).
1.8	0.47	69.266	Test speed 25 mm / min. Polyamide (secondary powder).
1.9	0.39	65.683	Test speed 25 mm / min. Polyamide (secondary powder).
2.10	0.65	70.037	Test speed 25 mm / min. Original.
Minimum	0.2	34.433	
Maximum	0.65	70.037	
The average	0.37	56.77	
Stand. reject	0.11	9.71	
Coef. variations	31%	17%

Figure 1. 3D model of the workpiece fixator (Type 1)

Figure 2. The horizontal arrangement of 3D models of fixators (type 1) in a virtual

Figure 3. Variant of automatic arrangement of products in chamber (vertical arrangement)

Figure 4. Conveyor belt bracket

Figure 5. The layout of bracket conveyor belt bracket in a virtual camera

Figure 6. Change in the mass of the fixator before and after the tests

Figure 7. Graph of changes in sample loads

Figure 8. Change in holder geometry before and after tests