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RESTORATION OF WEAR-OUT EQUIPMENT USING COMPLEX METHOD OF 3-D SCANNING AND PRINTING

Introduction. *Equipment restoration is a complex process that requires a comprehensive approach. Wear of parts and components of large-scale equipment leads to a halt in technological processes, reduced productivity, and sometimes to the complete breakdown of the entire production chain.* ***Problem Statement.*** *In most cases, on-site repair is impossible. However, modern CAD technologies not only allow assessing the extent of wear but also suggest a path to restoration. The widespread use of 3D printing has significantly simplified the process of creating individual parts. However, the high accuracy of the finished product largely depends on the quality of the model. Rapid acquisition of a highly accurate model is possible with the help of a 3D scanner. However, the extensive selection of 3D equipment, as well as materials requiring special conditions, significantly complicates predicting the quality of the finished product.* ***Purpose.*** *To examine the stages of repairing parts using 3D scanning and 3D printing. To provide accuracy values for the obtained models and the quality of finished parts using the example of a part made of semi-crystalline material PEEK.* ***Materials and Methods.*** *The economic feasibility of 3D printing worn parts is argued. Direct and indirect methods of restoration are considered. Accuracy values obtained when printing materials such as PAI2, PP, TPU, ABS, PEEK are provided.* ***Results.*** *The conditions for 3D printing polyetherketone PEEK are identified, as well as the optimal characteristics for obtaining a material with the highest wear resistance.* ***Conclusions.*** *The application of a comprehensive method for restoring worn parts using 3D printing and scanning is a promising and reasonable solution. However, despite the high accuracy and quality of the modern method, the analysis conducted shows the need to study the issues of fastening parts of worn elements and the adhesion of the materials used.*

Keywords: *3D printer, scanner, composite, restoration, equipment, technology, PEEK.*

Рассохін Д.О., Носовська О.В., Кокодей Д.В. Відновлення зношеного обладнання комплексним методом 3-D сканування та друку. *Реставрація обладнання – складний процес, який потребує комплексного підходу. Зношування деталей і вузлів великогабаритного обладнання призводить до зупинки технологічних процесів, зниження продуктивності, а іноді й до повного виходу з ладу всього виробничого ланцюга. У більшості випадків ремонт на місці неможливий. Однак сучасні технології CAD дозволяють не тільки оцінити ступінь зносу, але й підказують шлях до відновлення. Широке поширення 3D-друку значно спростило процес створення окремих деталей. Однак висока точність готового виробу багато в чому залежить від якості моделі. Швидке отримання високоточної моделі можливо за допомогою 3D-сканера. Однак великий вибір 3D обладнання, а також матеріалів, що вимагають особливих умов, значно ускладнює прогнозування якості готового продукту. Мета роботи – вивчити етапи ремонту деталей за допомогою 3D сканування та 3D друку, забезпечити значення точності отриманих моделей та якість готових деталей на прикладі деталі з напівкристалічного матеріалу PEEK. Аргументовано економічну доцільність 3D-друку зношених деталей. Розглянуто прямі та непрямі методи*

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реставрації. Надаються значення точності, отримані під час друку таких матеріалів, як PAI2, PP, TPU, ABS, PEEK. Визначено умови 3D-друку поліефіркетону PEEK, а також оптимальні характеристики для отримання матеріалу з найвищою зносостійкістю. Перспективним і доцільним рішенням є застосування комплексного методу відновлення зношених деталей за допомогою 3D-друку та сканування. Проте, незважаючи на високу точність та якість сучасного методу, проведений аналіз свідчить про необхідність вивчення питань кріплення деталей зношених елементів та адгезії використовуваних матеріалів.

Ключові слова: *3D-принтер, сканер, композит, реставрація, обладнання, технологія, PEEK.*

Description of the problem.

Introduction. Restoration and repair of worn-out equipment has a high economic effect. The failure of the components leads to a stop of operation of the entire mechanism. At the same time, in most cases, it is advisable to repair, which allows extending the service life of the mechanism [1]. Traditional restoration methods are processes including manual welding, CNC (Computer Numerical Control) machining, further grinding and polishing [2]. Moreover, such repairs are widespread due to the low cost of materials, as well as the ease of work. However, an increasing number of parts have a complex geometric shape, use high-strength materials, followed by surface hardening, which greatly complicates the restoration process. At the same time, the issue of on-site repair, considering the listed difficulties, makes such repairs impossible at all. To date, the issue of on-site repair has not been fully studied and is a complex relationship of the processes and technologies involved. This relationship is the focus of the current analysis.

Problem definition. The technology of repair in modern production conditions is demonstrated in Fig. 1.

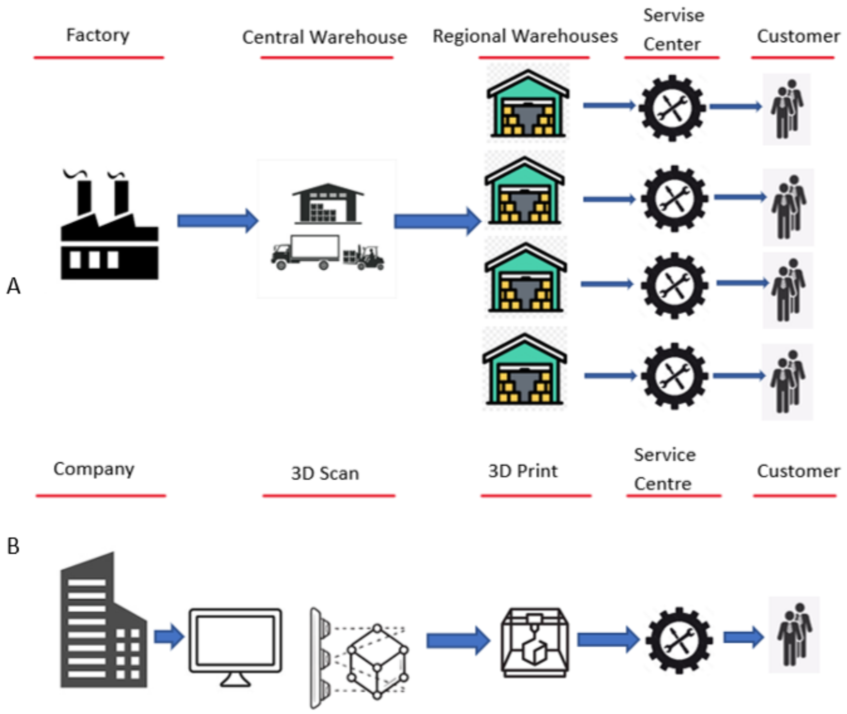


Fig. 1 – Scheme of repair and restoration of equipment: A) the classical scheme (production of new parts, warehousing, repair); B) a scheme using additive technologies (scanning a defective part, creating a 3D model of a defective part, repair)

In the classic repair scheme, a worn or damaged part is re-manufactured at the factory. At the same time, the technological process does not allow for a single production of such parts, which means that it is necessary to provide for a central storage of parts. The manufacturer is forced to cooperate with many consumers, in particular repair shops, to sell their products, which means that it is necessary to ensure regional storage of parts, considering the level of consumption. All this affects both the final cost of the part and the repair time. An alternative way of repair is the use of additive technologies. With this scheme, several stages are excluded, and the repair time is also significantly reduced. The use of additive technologies requires a high-precision analysis of the worn part, which can be achieved by 3D scanning. In this case, the resulting model will become the basis for creating a 3D model of the defective part, or it will allow for modernization by adjusting the geometry considering the nature of the destruction, replacing the material with a one with higher mechanical characteristics, or hardening the surfaces. At the same time, repairs can be carried out directly at the customer's enterprise, because additive technologies do not require complex and expensive equipment and machine tools.

Restoration of individual objects from composite materials using the 3D printing method compared with subtractive production is considered [3].

The manufacture of apart from a large workpiece by removing material requires a variety of specialized equipment. Machines for milling, turning, grinding operations. Each of the methods has its own advantages and disadvantages [4].

The positive advantages of additive manufacturing include the possibility of manufacturing parts of complex geometry, as well as in single-piece manufacturing. In addition, additive manufacturing has a low material consumption, obtaining a part without many additional mechanical operations, which in turn significantly reduces manufacturing time. The advantages of subtractive manufacturing compared to additive manufacturing are the high quality of the resulting surface, dimensional accuracy, and improved mechanical properties of the materials used. However, today this situation has changed considerably [5].

The aim of the article is to analyze modern methods of equipment repair using traditional and innovative approaches, including 3D printing and thermoset composites, to identify their advantages, limitations and potential applications in the industrial and domestic spheres.

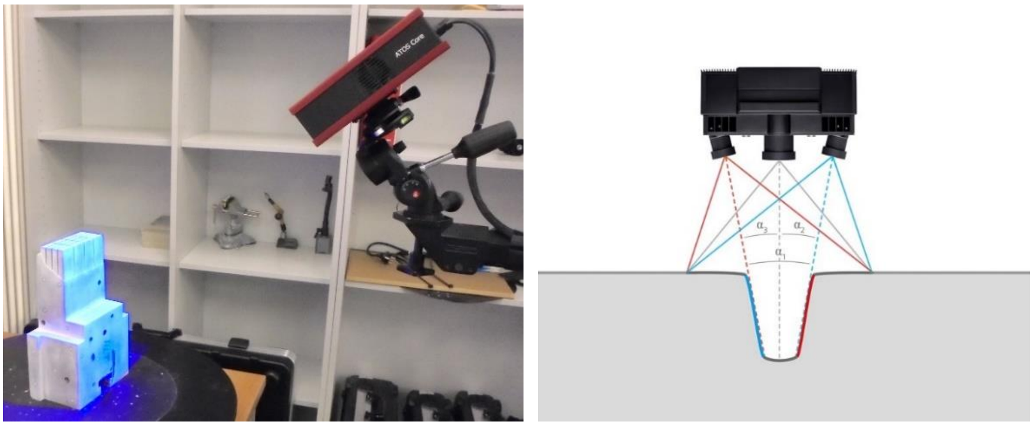
Analysis of recent research and publications. To date, additive technologies not only compete with traditional methods in terms of the range of materials used, but also surpass them in environmental and energy parameters. The application of additive manufacturing using the CLAD (Direct Additive Laser Manufacturing) process allows you to create parts with a thickness of less than 1 mm, in addition, this method allows you to repair parts, including metal materials and alloys. The study considered the option of creating apart from a titanium alloy Ti_6Al_4V, and compared the environmental impact compared to the traditional processing method. A laser additive manufacturing (CLAD) study showed a 70% reduction in environmental impact compared to CNC milling. The main impact was related to the production of powder. At the same time, a comparison of the cost of using the same allows us to conclude about the advantage of additive technologies. Comparison of the cost of restorations from composite materials obtained by 3D printing and subtractive methods in the medical field showed a significant excess of the average annual investment costs [3].

Thus, the use of 3D printing for dental restorations requires an annual investment of $186, while the use of subtractive methods requires from $875 to $1,284 annually. At the same time, the quality of the resulting products was comparable both for samples obtained by 3D printing and those obtained by milling. The waste ratio should also be considered, which for 3D printing was 73% and 90% for milled restorations.

However, the quality of the parts obtained by 3D printing directly depends on the accuracy of the 3D scanned model. There are two types of 3-D scanning. These are non-contact and contact scanning [6]. When contact scanning, it is necessary to ensure contact with the measured object. This may damage the surface of the object. At the same time, their use is limited due to the low processing speed. Non-contact measurement of objects allows you to obtain contour data of the measured object by triangulation. In this case, the laser that sends a beam to the surface of the object is reflected and captured by the detector, which in turn allows calculating the coordinates of each elementary unit of the surface. In this case, a cloud of 3-dimensional coordinates is created, and a model is built based on these digital data [7]. According to the types of measurement, scanning systems are divided into those operating in a plane or performing scanning with rotation. At the same time, markers are preliminarily applied to the surface of the part, allowing the photos to be joined. Non-contact 3-D scanning of objects is of great importance for the industry. Existing technologies make it possible to control the geometry of parts both at the final stage - a finished part, and during its manufacture [8]. In addition to changing the parameters of the part, the system can also register the wear of the machining tools [9]. A 3D scan performed on an already worn or destroyed part will allow you to determine the amount of wear. In this case, the curvilinearity of the worn surface will be considered in the model with a certain degree of accuracy. This will allow the CAD model to be built and tested and corrected. The effectiveness of 3D scanning is limited by existing shortcomings, some of which already have solutions:

1. There is no way to recognize the different materials used in one object.
2. The difficulty of obtaining a high-quality model of shiny, mirror, transparent surfaces. It is solved by using a white spray.
3. Errors in obtaining complex surfaces containing grooves, grooves in the object's body. It is solved by increasing the scan angle.
4. Necessity to use powerful computer technology. This is especially true for objects with large overall dimensions.
5. Errors during scanning, in which some surfaces are skipped. This is reflected on the model as holes. It is solved by additional editing of the finished model by means of CAD.

However, it should be noted that most of the problems are already successfully solved using modern computing equipment [5, 10]. The potential of 3D scanning devices is quite wide [3, 11]. Their diversity is subdivided according to the type of use into manual ones, which are widely used in architecture, medicine, and stationary ones, mainly used in industry [6-8, 12-14]. When scanning an object with a size of 1-300 meters, the scanning accuracy is 2-5 mm. With a scanning range of 0.3–1.5 m, the scanning accuracy is 0.1-1 mm [9, 15]. Such an order of scanning accuracy creates restrictions on the use in the details of engineering production. The use of specialized equipment makes it possible to improve the accuracy of scanning [10, 16]. The optical 3D scanner GOM ATOS Triple Scan II, when measuring the dimensions of an object under investigation with a diameter of 12 mm, showed a deviation from 0.7 to 1.45 μm (measuring volume MV100) (Fig. 2). After receiving a 3D model of the part, a decision is made on its creation or restoration. The choice of a repair method for a part largely depends on the nature of the operation, as well as the amount of wear.



a) b)

Fig. 2 – GOM ATOS Triple Scan 3D scanner a) in operation; b) principle of triple scanning (Source photo: Lometec)

Presentation of the main material. Modern methods of repairing worn parts use direct and indirect restoration methods [17]. Direct methods include laser beam melting (SLM), laser cladding (LENS) [18]. One of the effective methods for repairing damaged components is the method of layer-by-layer creation of a material by directing laser beams into a thin layer of powder [19]. Examples of such repairs are the restoration of corrosive wear of gearboxes in aircraft, corrosive wear of air pump housings, valve drives in the marine industry, etc. [20-24]. Efficient additive manufacturing methods also include bath polymerization, material extrusion [25], material spraying, powder bed melting [26-27], sheet lamination [28], direct energy deposition, and binder spraying [29-30]. Material extrusion is used the most widely. To date, the choice of filaments is presented quite widely (Table 1).

Table 1

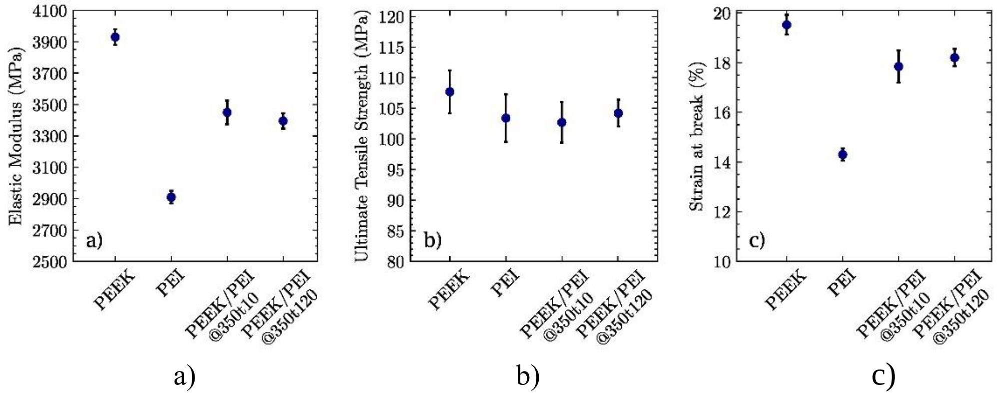
Used filaments in 3D printing with heat resistance up to 320°C

Operating temperature, °C	Amorphic	Semicrystalline
60	PCV	
80	PMMA	PA12
90		PP
100	PC	PA6.6, PA 6.10, PA6, PET
120	PS, ABS, SAN	PA4.6, PVDF, PPA
160	PSU	
180	PPSU, PES	
240		LCP, PPS, PTFE, PFA, PFE, PCTFE
250		PEEK
260	PAI	
300	PI	
320	PBI	

The material extrusion method, also known as FDM (Fused Deposition Modeling) or FFF (Fused Filament Fabrication), is one of the most common and affordable additive manufacturing methods. It is based on heating and pushing a plastic material through a nozzle, creating an object layer by layer. The FDM process begins by loading a filament of plastic material into the printer. The filament is then heated to a certain temperature to become malleable and formable. This molten material is then extruded through a nozzle and applied to the work surface, where it cools and solidifies to form a layer of the object. Once one layer is completed, the platform is lowered by a fixed amount and the process is repeated to create the next layer. This cycle repeats until the entire object is completed. The FDM method has several key advantages. These include affordability and ease of use. FDM printers are available in a variety of price points and are easy to customize, making them accessible to a wide range of users. In addition, FDM printers are compatible with different types of plastic materials including PLA, ABS, TPU and many others. This allows you to choose the right material depending on the requirements of the product. Due to its ability to create dense and strong layers, FDM can be used to produce functional prototypes, components, and parts. In doing so, the FDM method is widely used in a variety of applications including prototyping, engineering modeling, education, and small batch production of parts. It is also used in the creation of customizable products and unique parts that require a customized manufacturing approach.

The creation of parts of metal parts involves the use of materials that are similar in mechanical properties. Polyetherketone PEEK can be attributed to this type of materials. This semi-crystalline polymer is actively used in bioengineering, in the creation of implants, in mechanical engineering, etc. One of its advantages is its high melting point, which also allows heat treatment. The quality of the resulting layer depends on the settings and characteristics of the 3D printer. These values include nozzle and chamber temperature, base plate temperature, layer height and print speed, and cooling mode.

PEEK has several characteristics that make it an attractive material for additive manufacturing. Its high temperature resistance allows it to withstand high temperatures of up to 250°C, making it ideal for applications requiring resistance to high temperatures. At the same time, the material has high mechanical strength and stiffness. PEEK is resistant to a variety of chemical attack, including oils, solvents, and aggressive chemical environments, and is also highly corrosion resistant. Further improvement in wear resistance lies in the addition of microfillers as well as nanoparticles in the PEEK matrix. Carbon nanotubes, carbon fibers introduced in the matrix show significantly enhance the mechanical properties. In addition, it has good biocompatibility, which greatly expands its application area. As the study shows [31], PEEK printing is carried out at a nozzle temperature from 350 to 440°C, a bearing surface temperature of 100-150°C and a chamber temperature of 90-160°C. In this case, the temperature is crucial and failure to comply with the regime can lead to cracking of the part, its warping. At the same time, this material has high mechanical characteristics. Thanks to carbon fiber reinforcement (CF/PEEK), this thermoplastic material has high damage resistance as well as creep and fatigue resistance. Flexural strength tests were 140 MPa [31]. This material has wide limits of optimization. It was revealed [32] that the use of preheating (C3D/PEEK) before hot pressing, as well as the optimization of the production process and processing parameters, can increase the bending strength up to 500 MPa. The elastic modulus of pure PEEK reaches 3900 MPa, the ultimate tensile strength is 108 MPa, and the elongation at break is 19% [33] (Fig. 3, Table 2, 3).



a) b) c)

Fig. 3 – (a) Modulus of elasticity, (b) tensile strength, and (c) elongation at break of pure PEEK and PEI polymers and MLP PEEK/PEI treated at 350°C for 10 and 120 minutes [34]

A separate issue in the production of parts or segments during restoration is the dimensional accuracy, as well as the roughness of the resulting surface [20, 34-35]. Using the example of creating cams by CNC machining and a 3-D printer, the same error values in diametrical dimensions were obtained. At the same time, the average roughness Ra of cams made of polylactic acid (PLA) material printed on a 3D printer was 20 times higher than that of milled aluminum cams (no grinding was carried out). Average roughness values were 10.41 µm for printed cams and 0.5 µm for milled cams. Comparison of the surface roughness of parts obtained from various materials by FDM and SLS 3D printing allows us to conclude that the PEEK material has the lowest roughness values – 7.7 µm [36]. And laser polishing reduces these values to 0.13 µm.

Table 2

3D printing method and initial roughness of various materials measured with a band pass filter at 8-320 µm spatial wavelength [33]

Material	Printing method	Roughness after printing	T_{act}, inspected range	t_w, inspected range
PAI2	SLS	10.2 µm	180-270°C	10-200 s
PP	SLS	16.9 µm	120-200°C	20-160 s
TPU	SLS	39.5 µm	170-220°C	20-240 s
ABS	FDM	18.5 µm	180-220°C	20-140 s
PEEK	FDM	7.7 µm	300-370°C	600-1800 s

Table 3

Achieved roughness for various laser polished materials measured with a band pass filter at 8-320 µm spatial wavelength [33]

Material	Temperature set point for laser polishing	Interaction time for laser polishing	Roughness after laser polishing
PAI2	210°C	200 s	0.61 µm
PP	180°C	60 s	0.59 µm
TPU	200°C	40 s	0.12 µm
ABS	220°C	60 s	0.24 µm
PEEK	340°C	1800 s	0.13 µm

The use of composite PEEK is due to its potential as an engineering material with high thermal stability, chemical resistance, strength, and machinability. The mechanical properties of PEEK material are highly dependent on printing conditions, in particular nozzle temperature and printing speed. To date, the PEEK material has been studied quite well. Melting point 330-385°C, creates conditions for heat treatment. The minimum wear rate for the sample in the annealed state is known – $1.37 \cdot 10^{-6}$ mm^3/Nm. The combination of annealing and yarn orientation makes it possible to achieve an elastic modulus of 3-4 GPa and a tensile strength of 90-120 MPa. The following studies of the material for friction and wear are known. Abrasive dry wear was studied [37] by the author for pure PEK and reinforced with carbon fiber APC2 and aramid fiber K49/PEEK. The effect of fiber orientation on the wear mechanism was observed. The results showed the highest wear resistance of the composite material reinforced with aramid fibers oriented normally to the contact surface and carbon fibers oriented in parallel. All this makes polyetherketone PEEK a versatile material, the use of which is possible in solving a wide range of engineering problems.

Conclusions

Modern development of technologies allows you to perform equipment recovery in various ways. The authors analyzed the methods of such restoration using 3D printing in relation to the problem of restoring the surface of damaged parts at the site of operation. The technical means and materials that make it possible to repair parts made of metals while maintaining mechanical characteristics are determined, and the problems and shortcomings of the proposed technologies are analyzed. However, the issue of fixing the restored parts on the main part remains unexplored. The study of adhesion for various materials, the nature of surfaces, operating conditions is a promising direction for the further development of the considered technology.

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