DEVELOPMENT AND RESEARCH OF EQUIPMENT FOR PROCESSING OF GRANULATED POLYMERIC MATERIALS VIA 3D PRINTING FOR THE NEEDS OF LIGHT INDUSTRY

Oleh Polishchuk, Petro Zozulia, Andrii Polishchuk, Pavlo Maidan, Mykola Skyba, Nazar Kostyuk, Andrii Kravchuk and Olha Kravchuk

Khmelnytskyi National University, Instytuts'ka str. 11, Khmelnytskyi, Ukraine
opolishchuk71@gmail.com

Abstract: *Current state of 3D printing in various industries and prospects of its application in light industry have been analyzed. It has been revealed that pressure and productivity at the outlet of the extruder, as well as quality of melt preparation in 3D equipment for processing polymeric materials in the form of granules depends on the geometric dimensions of the extruder and auger's working tool. Mathematical modeling of heating process of the polymeric material in the extruder has been done, thermal diagrams have been obtained, which allow to predict the temperature distribution in its different sections. A 3D printer with FMD technology for printing with polymer granules as a raw material has been developed. Resistance to destruction by a wedge-shaped blade of sewing materials with polymeric coatings applied to them by the method of 3D-printing has been researched.*

Keywords: *3D printer, 3D print, polymeric materials, waste, installation, auger, heating mode, sewing and footwear materials.*

1 INTRODUCTION

Additive technologies are one of the main world trends mentioned in the context of the new industrial revolution. Market of goods manufactured with use of such technologies has practically not been yet formed, has no clear boundaries, varies between 20-30% and tends to grow rapidly [1, 2].

It is a known fact that there are several methods of 3D printing, but they are all derivatives of additive technology for manufacturing [3]. Regardless of what 3D printer is used, the product is manufactured via layer-by-layer application of a thin reel of molten material extruded from the extruder on the working platform. The task of the printer is to move the extruder in exact accordance with the digital model. Therefore, the printed physical object totally corresponds to its virtual prototype, created with the help of graphic editors for 3D computer design. The output is details of a complex geometric shape produced in a short time [1, 4].

Modern products are characterized by complexity of construction, a large number of parts and components. For instance, footwear, especially sports type, has a complex geometric shape, may include active elements in the form of tubes, rods, plates, springs and other parts that increase its performance. Such parts are designed to absorb shock loads that occur during various physical exercises, running, jumping, as well as to promote repulsion, which improves performance of athletes in various sports. These elements can be constructively made as a single unit with a sole or in the form of various inserts: polymer or metal ones [5]. In addition to the issues related to the design of polymer products of complex geometric shapes, there are also issues related to their production. To make complex shapes of product parts, new methods of their manufacturing need to be created. Therefore, one of the modern ways to resolve this problem is 3D printing. Having analyzed the use of 3D printers in various industries, we can conclude that the greatest potential of 3D equipment lies in production of industrial goods. Light industry, in particular sewing and footwear, is no exception to this [5, 6]. Some existing consumables for 3D printing are quite suitable for production of clothing, footwear and their elements. Moreover, their range constantly increases. Materials with the required technical parameters appear [6]. All this contributes to the introduction of 3D printing in light industry. Nowadays, the use of 3D printers in mass production is limited due to relatively high cost of equipment and duration of the manufacturing process itself. The technology of 3D printing can be successfully used in production of small-scale and individual products, as production of high-value equipment in this case becomes unreasonable [5].

In paper [1], modern 3D-printing and 3D-printers technologies have been analyzed and systematized. A generalized classification of 3D printers has been developed, which gives a complete idea and characteristics of each type, purpose, etc.

Moreover, a new type of 3D printing was listed in this classification for the first time, namely 3D printing with polymer granules, which will become competitive in a rapidly developing industry along with other types of 3D printing and consumables. This type of printer is under development. One of the main advantages of this type of printer is the ability to reprint parts with granules from waste that was obtained during previous printing. Therefore, the cost of filament can be reduced through the use of secondary raw materials. Thus, it is unreal to obtain a rod equal in diameter from secondary raw materials, simply due to properties of the melt being inhomogeneous in mass; hence it leads to uneven pressure in the industrial extruder, uneven plasticity of the melt and its shrinkage. Respectively, during printing, such rod will behave completely unpredictably. During the first stage of processing of the output polymer and the first service life of the polymer chain there are irreversible changes caused by chemical effects, thermal, heat and photooxidative destruction, which leads to the appearance of active groups. These groups in subsequent processing are able to trigger oxidation reactions. Respectively, the smaller the number of processing, the better the material is, which, as a result, will affect quality of the future part or product. However, in the case of polymers processing, it is possible to create a new material with new properties by adding to their composition various admixtures, dyes, plasticizers to improve elasticity, plastic deformation, frost resistance, impact strength, decrease viscosity to improve their further processing and exploitation [5].

Primary raw material for powering 3D printer extruders is a rod made of polymeric material of a certain diameter. Polymer granules are used as raw materials to produce the rod. This process is long, which is unacceptable in today's competitive environment.

One of the main disadvantages of 3D-rod printing is that at the production stage the polymer is already subjected to temperature heating, which leads to loss of its physical and mechanical properties. Therefore, 3D printing using granules of the material is relevant. Printing using granular material is ideal in cases where additive and subtractive (rapid prototyping) methods of parts production can be combined. This will enable to quickly print the part on a 3D printer.

Growth of production using polymeric materials steadily leads to increase in their share in waste and the issue of recycling becomes integral for the issue of disposal of other wastes of human life. Modern polymeric materials based on various plastics, fibers and elastomers are used in various fields. Light industry is no exception to this [7, 8]. Therefore, the issue of polymer recycling and their subsequent use in light industry is an urgent task.

2 EXPERIMENTAL PART

2.1 Research equipment

To process polymers with different properties, equipment that would meet the necessary requirements, i.e. has optimal geometric parameters and thermal modes, is required. In order to conduct experimental research, a device was developed that allows printing 3D parts with granular or crushed polymeric materials obtained from waste garment and footwear production. Principle of operation of such equipment is as follows. The crushed polymer granules are placed into hopper 2 (Figure 1) or the loading area. After that, the raw material is fed by a rotating auger 4 in the heating zone for melting and subsequent extrusion. The polymer is melted and extruded in the form of a thin reel on the working platform. Further on, by layering the molten polymer material, a physical object is formed, i.e. a previously modeled part.

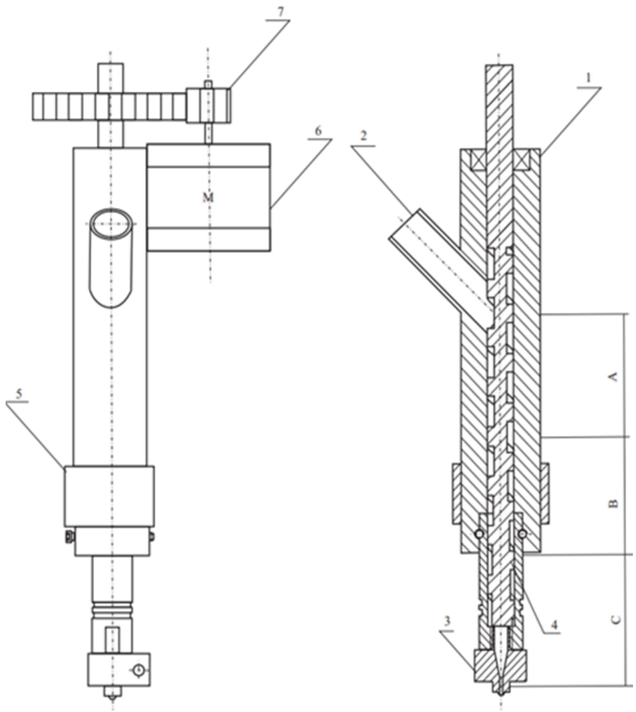


Figure 1 General scheme of the experimental device for processing of polymeric masses: 1 - body; 2 - loading hole; 3 - unloading hole; 4 - auger; 5 - heating element; 6 - stepper motor; 7 - gear; A - loading zone; B - melting zone, C - homogenization zone

To ensure the necessary movement of the material, the conditions for moving the solid material from the loading zone to other zones of the extruder and filling the interturn space in the auger are of great importance. A complete analysis of the movement of solid particles in a traditional single-auger extruder was done in paper [9] for the first time. In order to determine the conditions for the movement of polymeric material from the loading zone to the extrusion zone, experimental studies were conducted, which made it possible to understand how the interturn space in the auger is filled with polymeric material (Figure 2).

This enabled to establish the stages of transformation of solid-crystalline-state polymer particles into a viscous state of the finished material for layering by 3D printing to obtain a physical object (Figure 3).

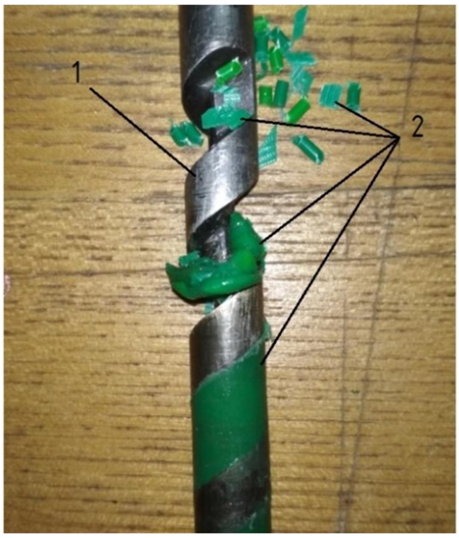


Figure 2 Photo of auger's interturn space filling with polymeric material

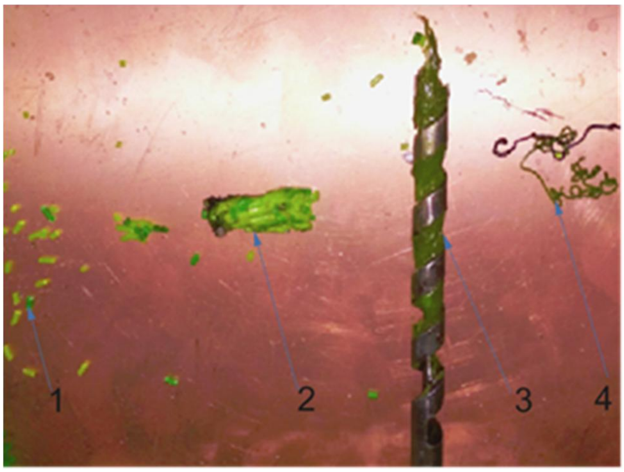
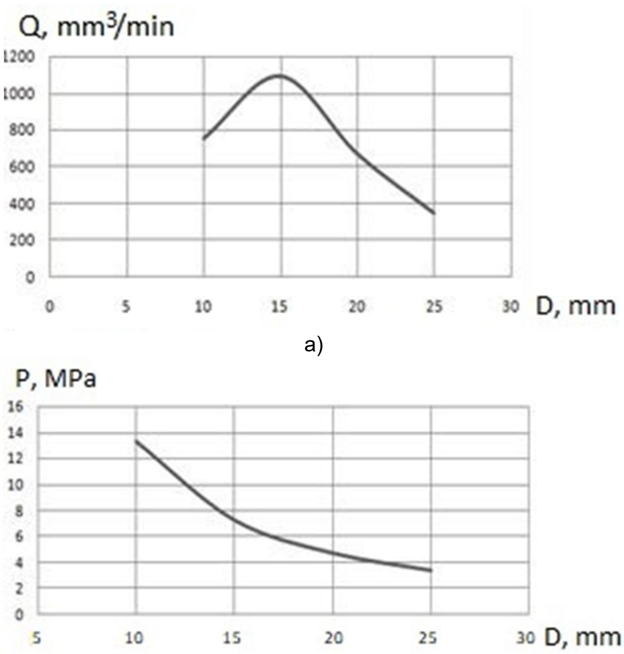


Figure 3 Stages of polymeric parts transformation: 1 - polymeric parts, 2 - start of adhesion stage melting of polymeric particles into a single unit, 3 - working auger's interturn space filling during operation, stage of polymeric parts homogenization into a single unit, 4 - output material after extrusion

The analysis of the obtained samples allowed us to reveal that at first, at normal temperature, a long polymeric plug is formed, which is pushed through the auger channel. The length of the plug must be large enough so that the pushing force resulting from the longitudinal movement allows the polymer to move into the melting zone. Transportation of polymeric materials of different shapes and sizes (crushed waste) or powders with poor flowability and low flow weight in the supply area is quite a difficult task. Therefore, when designing equipment for 3D printing with polymer granules, it is necessary to take into account all the forces that affect the printing process of parts. This, in turn, will allow to calculate optimal parameters of the device for processing polymer masses (Figure 1) and ensure uninterrupted operation of the 3D printer [10].

The defining parameters in the extrusion of polymers are the pressure and productivity at the outlet of the extruder as well as the quality of melt preparation. These parameters significantly depend on the design and geometry of the auger.

Productivity of process Q and melt pressure P from auger diameter D, length of auger working zone L from productivity of process Q, melt pressure P from length of auger working zone L, melt pressure P from density (shear rate) of material, auger productivity Q_w from parameters of density (shear rate) of the polymer [8, 9] has been calculated. On the basis of the received data the corresponding dependences of certain sizes have been constructed. For example, Figure 4 shows graphs of the dependence of productivity of the process Q and the melt pressure P on the diameter of the screw D. The calculations made it possible to determine optimal geometric parameters of the device to process polymer masses on the basis of which it was manufactured.



a)

b)

Figure 4 Dependency graph: a) process Q productivity on diameter of auger D; b) melt pressure in extruder P on diameter D

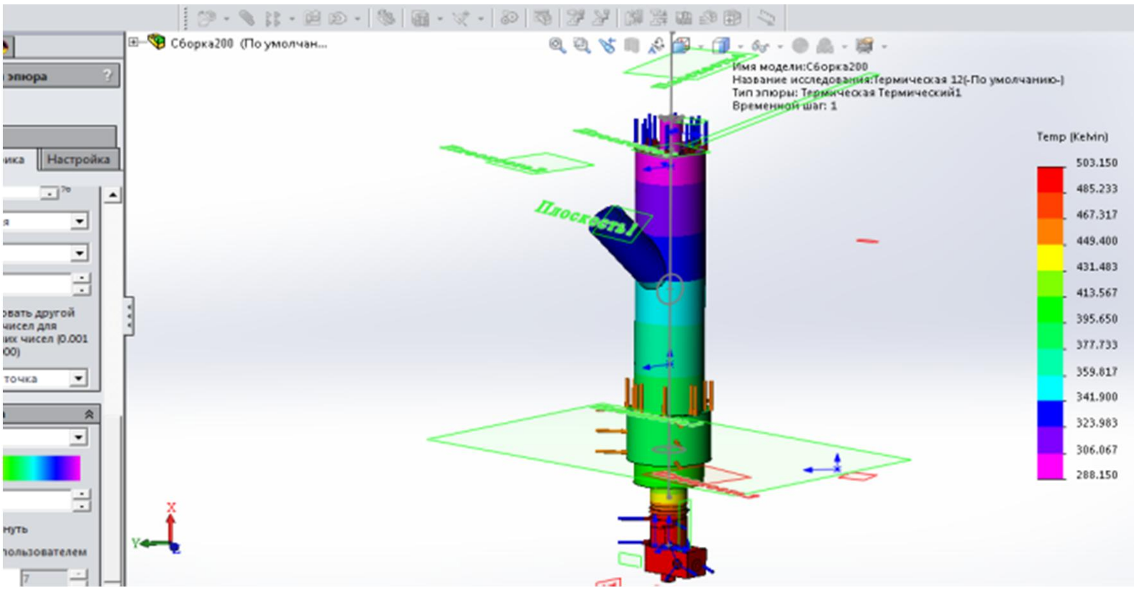


Figure 5 Distribution of temperatures along the device

An important step in the introduction of energy-saving (energy-saving) equipment for processing filaments by extrusion is modeling of the heating process, which would allow to control heating modes of the extruder in its working areas [11].

In this regard, there is a need for mathematical modeling of heating modes of the extruder before the stage of the direct process of production and the study of temperature distribution in the installation depending on the power of the heaters in different areas.

For this purpose, mathematical modeling of the heating process of polymeric material in the extruder was performed; a system of equations and a thermal diagram (Figure 5) of the temperature distribution along the entire length of the extruder were obtained.

This approach allows to predict the temperature distribution in different parts of the real device and selects optimal temperature modes when performing the process.

Based on the thermal diagram, it can be concluded that the physical object, i.e. the part to be printed, will have sufficient and uniform heating at the specified temperatures.

Therefore, the necessary plasticization and homogenization of polymeric materials in different areas of the extruder will be provided.

Installation for experimental research was developed on the basis of an inkjet 3D-printer with FMD-printing technology (Figure 6).

In this installation, the print head for polymer-rod printing was dismantled and a developed device for processing polymer masses entering the extruder in the form of granules was installed (Figure 7).

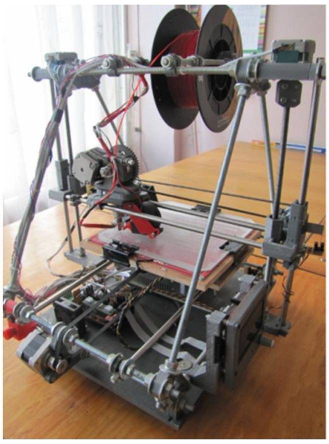


Figure 6 Basic model of 3D printer with FMD printing technology

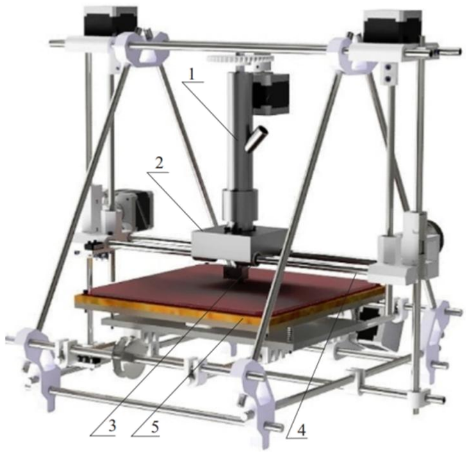


Figure 7 General scheme of the installation with a device for processing of polymeric masses: 1 - extruder; 2 - extruder installation fastening; 3 - linear motion bearing; 4 - device motion shaft; 5 - working surface for cooling of output material

2.2 Methodology

Experimental studies of the application of polymeric material by extrusion on materials used in the garment industry were carried out using the developed and manufactured installation [13, 14]. Samples of various sewing materials were selected, in particular denim, cashmere and synthetic fabrics [12]. To obtain a 3D coating, as a feed source for the extruder, waste from ABS plastic was used. Technical characteristics of materials are given in Table.1. Figure 8 shows the obtained samples of sewing materials.

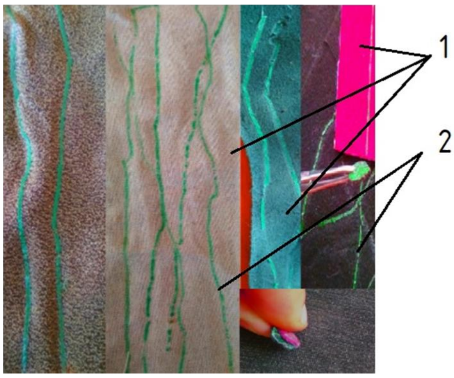


Figure 8 Samples of sewing materials with applied polymer layer: 1 - material; 2 - polymer coating

The obtained samples of materials with a polymer coating have been studied in regards to resistance to destruction by a wedge-shaped blade. For this purpose, an experimental setup was developed, which is presented in Figure 9. The principle of operation of the installation is as follows. Beforehand, a punch 2 was screwed into the rod 1 of the press, and a stand located on a strain gauge was placed in the lower part of the press. This strain gauge allows to measure the cutting force of the material. Another strain gauge connected to the punch allows to determine the volume of a dip of the punch into the material. The material, in its turn, is placed on the stand. The effort required for cutting the material is created via means of the handle of the press. The analog signals generated in the strain gauges are amplified, fed to an analog-to-digital converter, converted to a digital signal and fed to a computer. With the help of the installed software the signals are processed and graphs of dependences of technological efforts of cutting F_{cut} of material on depth of the dip of the punch Δ are constructed.

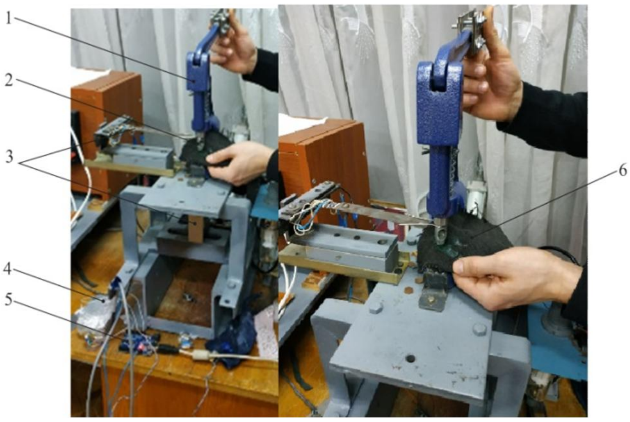


Figure 9 Experimental installation for the research of materials resistance at destruction with a wedge-shaped blade: 1 - cutting press; 2 - working organs (punch and stand); 3 - strain gauge; 4 - amplifier; 5 - analog-digital converter; 6 - material sample

3 RESULTS AND DISCUSSION

The results of the research on resistance of sewing materials to destruction by a wedge-shaped blade are shown in Figure 10. The graphs show the dependence of the technological cutting forces F_{cut} for different materials studied without and with coated coatings on the depth of the dip of the punch in the material Δ.

From the obtained diagrams it is seen that the technological effort at cutting the material with a punch reaches its maximum value at full dip of the punch in the material to a thickness Δ.

Analysis of the obtained experimental data showed that after applying the polymer layer on the material, its resistance to destruction increases, as shown by the results given in Table 2.

Table 1 Types of sewing materials fabrics used in the experiment

№	Type of material	Application material	Material thickness prior to application of polymer layer [mm]	Material thickness after application of polymer layer [mm]
1	Cashmere	ABS	2.17	2.27
2	Synthetic fabric (with interfacing)	ABS	1.20	1.69
3	Denim	ABS	1.69	1.93

Table 2 Value of material destruction maximum efforts

№	Sewing material	Coating material	Destruction effort prior to coating F_{cut} [H]	Destruction effort after coating F_{cut} [H]
1	Cashmere	ABS	294.79	342.48
2	Synthetic material	ABS	301.10	326.57
3	Denim	ABS	366.35	414.13

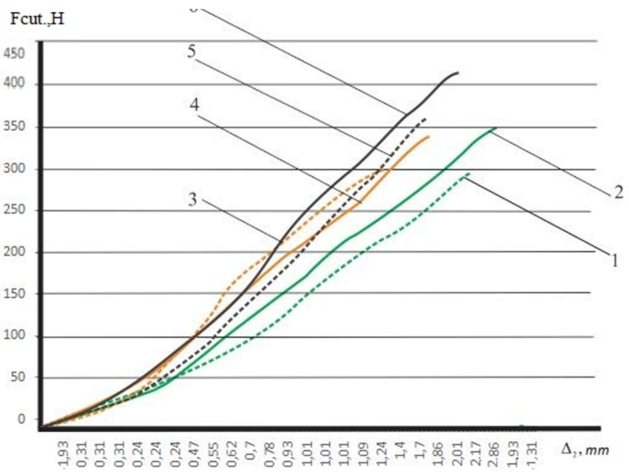


Figure 10 Graphs of F_{cut} technological effort dependencies for various materials on depth of plunger's dip into the material *Δ*: 1 - cashmere with no polymer layer; 2 - cashmere with polymer layer; 3 - synthetic material with no polymer layer; 4 - synthetic material with polymer layer; 5 - denim with no polymer layer; 6 - denim with polymer layer

4 CONCLUSIONS

The use of 3D printing technology can solve a number of problems in light industry, in particular in clothing and footwear industries. Introduction of this technology in mass production of clothing and footwear is an urgent task.

The defining parameters in the extrusion of polymers are pressure and productivity at the outlet of the extruder, as well as quality of melt preparation. The dependences of the process productivity *Q* and the melt pressure *P* on the screw diameter *D* have been obtained.

Mathematical modeling of heating process of the polymeric material in the extruder and the obtained thermal diagrams allow to predict temperature distribution in different parts of the device and selects optimal temperature modes when performing the process.

On the basis of theoretical and experimental research, a 3D printer with FMD technology for printing with polymer granules as a raw material has been developed, which allows the use of crushed polymer waste generated in production of clothing and footwear.

The obtained results of research on resistance of sewing materials to destruction by a wedge-shaped blade showed that after applying a surface layer of polymer on material, resistance of materials to destruction, their durability, and wear resistance increase.

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