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PROCESS SIMULATION OF HOLE MANDRELLING IN STEEL AIRCRAFT PARTS

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The processing technology of steel structural elements of aircraft parts is especially important since, if improperly processed, this material can be subjected to weathering, causing corrosion. Furthermore, special attention is paid to the walls of holes used for bolting. Since holes can become stress concentrators, the paper proposes to strengthen them by implementing the SPD (surface plastic deformation) method. The article describes the simulation of the mandrelling process, which is more efficient and less traumatic. Therefore, changes in the walls of holes as a result of deformation are shown, which occur after the process of hole mandrelling.

Keywords: surface plastic deformation, hardening, hole mandrelling, bolting, lubrication, mandrel

1. Introduction

The fields of modern aeronautical and mechanical engineering are always in search of ways to improve the wear resistance, durability as well as reliability of parts and assemblies. The use of high-strength alloys does not always provide the best solution to this problem, since they entail a number of associated disadvantages. The most successful solution to increase wear resistance, durability, reliability and other properties of a part is to strengthen its surface layer [1]-[3]. This layer is the first to perceive loads, resists them and protects the base material. Given that the quality of the surface layer ensures reliable operation of the part, more stringent requirements are imposed on this layer than on the base material of the part.

To improve the quality of and eliminate various defects in the surface layer, surface plastic deformation (SPD) techniques are used [4]. Although the application of SPD methods effectively increases the life cycle of free unfilled holes and bolted holes, SPD methods are not fully implemented in production due to the high cost, low productivity and limited technological capabilities of the process as well as the availability of devices for strengthening.

In general, as the quality of the part increases, the standard of modern air transport will rise and economic efficiency be achieved.

In aircraft designs from the 20th century, the amount of steel used accounts for about 10% of the weight of an airframe. The main advantages of using steels are their high modulus of elasticity, relatively low price, good degree of interchangeability and operational reliability. Corrosion-resistant steels in modern aircraft with a long service life are increasingly replacing medium alloy steels, which enhances the reliability of their parts. Steels of this class are used to manufacture welded and non-welded parts of aircraft, engines and units operating at temperatures of up to 800°C. For the purpose of modelling, a material from this class was used, namely corrosion-resistant austenitic chromium-nickel steel.

2. Features of using bolted joints

In the parts of helicopters and aircraft, threaded joints are most widely used. Bolted joints are also widespread in the airframes of aircraft and helicopters [5].

Fatigue failures are a common cause of airframe failures. Up to 75-80% of all fatigue failures begin at the bolted joints between structural elements of airframes. Measures are being developed to increase the longevity of these compounds [6].

The applications of structural elements are set during the design phase, implemented in specific technological solutions during their manufacture and maintained throughout their operation. Therefore, all factors that determine the applications of bolted joints are

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divided into three groups, that is, design, technological and operational, which are presented in *Figure 1*.

Approximately 70% of the labour intensity in the manufacture of joints is spent on the formation and processing of bolt holes. The holes are formed using drills, countersinks, reamers and broaches. Due to the limited amount of space in which work can be done in these holes, it is necessary to reduce the cross-sectional dimensions of the cutting tool, thereby diminishing its rigidity and increasing the likelihood of vibration while cutting. Furthermore, retraction of the tool from the geometric axis of the part becomes problematic. Holemaking is further complicated by poor conditions with regard to chip evacuation.

Great difficulties arise when processing deep holes. In practice, the precise machining of cylindrical holes is more complex than machining their outer cylindrical surface.

Observations of the surface layers of various parts show that they are often weakened by external damage: cuts, microrelief scratches and traces of corrosion. The surface is the boundary of the metal, moreover, it is of reduced strength due to the damaged integrity of the crystalline grains during machining. The smallest microscopic scratches on the surface of the machined part can lead to its premature failure since they spread into the metal section under the action of dynamic loads, even when relatively small external loads are applied.

It has been shown that stress concentrators such as transverse holes located in plates, shafts and connecting rods serve as locations for the formation of fatigue cracks. Strengthening the zone with such holes increases the fatigue strength and localizes the sites of fatigue crack initiation [7]. The application of complex aggregates is limited to 10-20% of their maximum level of implementation due to the presence of stress concentration in the holes. Furthermore, 60-70% of this figure, that is, the main reason why complex aggregates are not implemented, is due to the presence of cylindrical smooth holes of small and medium diameters without coatings.

The application of parts and holes can be increased [8] by carrying out the following activities:

- improving the quality of hole processing;
- applying advanced processing methods that do not place the surface layer under tensile stress;
- bimetallizing holes;
- selecting the optimal ratio of tensions when setting the bolt in the bolt hole and the axial compressive force;
- chemical-thermal treatment;
- design optimization;
- processing by SPD methods.

Experimental methods for choosing rational technological parameters for the hole mandrelling process in steel aircraft parts require significant financing and high material costs, moreover, are time-consuming. The current level of development of computer technology and software facilitates numerical simulation of this process by the finite element method (FEM) [9]-[12]. The purpose of this work is to determine the rational technological process parameters of hole mandrelling in steel aircraft parts by a numerical simulation.

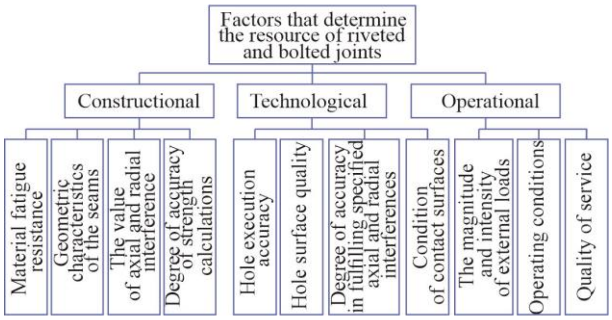

Figure 1. Classification of factors determining the applications of bolted joints

2.1. Possibility of hardening holes by the SPD method

Considering its problems, the possible methods of strengthening holes by the SPD method are analysed. Certain types of surfaces are subjected to their own hardening methods. To harden holes, the most commonly used methods are mandrelling, rolling and shot blasting.

Although shot blasting of metal is one of the most popular mechanical technologies, it cannot be implemented with a slipway assembly of units.

The method of hardening the surfaces of holes by rolling is quite effective, however, requires expensive equipment. Furthermore, usually only one side of the part can be treated when using slipway assembly, which significantly complicates the use of this hardening method.

Hole mandrelling is a method of hardening holes carried out by smoothing broaches or rolling tools referred to as mandrels. During hole mandrelling, the tool, that is, a mandrel, is pushed through the hole with a slightly smaller diameter compared to the tool itself. As a result of plastic deformation, the diameter of the hole increases, the processed metal layer in the hole is hardened and any uneven areas of the surface are levelled so the surface of the hole becomes very smooth [13]. The stress the surface of the hole is subjected to during mandrelling is, in most cases, compressive, which has a favourable effect on the structure of the layer of metal on the surface and the operational properties of that surface. Since plastic deformation usually occurs near the layer of metal on the surface when holes are mandrelled, any changes to the metal structure do not penetrate particularly deeply. Mandrelling is carried out without the use of finishing and polishing materials, so harmful particles of abrasive grains do not penetrate its surface.

Portable and stationary presses are used for mandrelling. Universal equipment is used as stationary presses. To implement the mandrelling process by complying with the co nditions of a slipway assembly, it is necessary to use pneumatic impulse hammers [14]-[15], which are the most profitable as such devices improve working conditions for operators by providing ease of use and maintenance. Furthermore, they offer a significant reduction in energy consumption being light weight and small, moreover, as a result, are very reliable, stable, economical as well as function in a cyclic operation.

Lubrication also plays an important role in mandrelling. The wrong choice can lead to a significant deterioration in the quality of the processed surface, an increase in the mandrel force and a decrease in the durability of the mandrel [16]-[18]. Mandrelling without lubrication leads to molecular adhesion of the metal being processed and the tool, causes metal to stick to the tool and can lead to mandrel hardening in the hole. When choosing a lubricant for the mandrelling process, it is necessary to ensure that the best surface finish is produced. Lubrication during mandrelling can be considered satisfactory if the conditions required for fluid friction are maintained between the rubbing surfaces throughout the entire process to help reduce traction and mandrel wear as well as improve the cleanliness of the processed surface. When steel is mandrelled, vegetable oil (linseed oil), machine oil or oleic acid is chosen as a lubricant.

2.2. The essence of the hardening process

According to the design of the mandrel, different types are used. Mandrels of all types, within the working area of their profile, have an intake part that performs the main work of metal deformation; a calibrating (cylindrical) part which increases the wear resistance of the mandrel and improves the quality of the processed surface; and a back part which is designed to reduce frictional forces during mandrelling. The design of the mandrel and its elements are shown in *Figure 2*.

Plastic deformation of the surface of the hole during mandrelling occurs due to the fact that the maximum diameter of the mandrel is greater than that of the hole to be hardened by a value referred to as the tension. The quality of processing and the value of the tension depend on a number of factors, e.g.:

- the material of the part as well as its physical and mechanical properties;
- the initial state, namely the accuracy of the shape, its dimensions and the quality of the surface of the hole;
- the material, shape and geometric dimensions of the working area of the tool as well as any possibilities to make adjustments;
- the feed pattern of the tool and part holding;
- heating of the tool and the processed material.

As the main parameter, the tension of mandrelling plays an important role, which is the difference between the initial nominal dimensions of the contact surfaces of the tool and those of the hole in the workpiece cross-section deformed by the mandrel. If the tension is less than necessary, then once the mandrel has been pushed, the surface layer of the metal will almost completely return to its original position in which it was before processing and no residual deformation will occur.

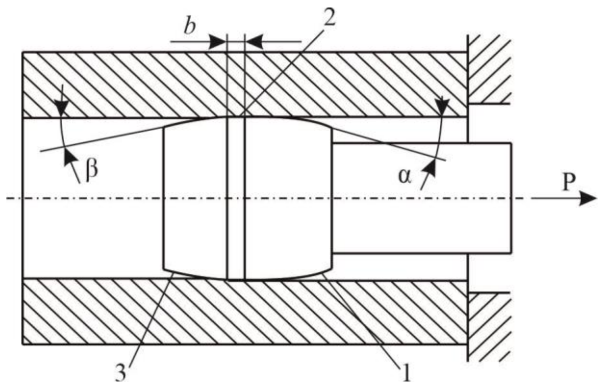

Figure 2. Construction of the mandrel:
α cone angle of the intake; β inverted cone angle; 1 the intake; 2 calibrating (cylindrical) part;
3 outlet part

However, should the tension be excessive, plastic deformation will result. As the tension increases, roughness decreases, but if the tension is too high, then the mandrelling process will be more difficult, since as the tension increases, the pressure applied on the part by the tool and the coefficient of friction increase. This usually leads to mechanical damage to the surface being hardened and excessive heating of the part which causes the structure of the material to change.

Under the influence of frictional forces and the normal amount of pressure applied by the mandrel, a complex stress state is created in the metal surrounding the hole, thereby moving the plastic metal wave. in the hole ahead of the mandrel during mandrelling. The height and shape of the generated wave depend on the material being processed, the tension of the mandrel, the wall thickness of the workpiece, the lubricant used as well as the shape and cone angle of the mandrel. The greater the pressure applied by the mandrel on the metal within the intake cone (and the frictional forces corresponding to this pressure), the larger the plastic wave formed in front of the mandrel.

3. Simulation of the hole mandrelling process

3.1. Preparations

Simulation of the mandrelling process that aircraft parts made of high-strength steels are subjected to was carried out using the Simufact Forming simulation tool. SOLIDWORKS and Compass 3D software were used as auxiliary programs for simulating the geometry of all the necessary parts for modelling the process. The first stage consisted of development of the geometry of the mandrel, support and mandrellable plate pack.

According to the design scheme, a single-tooth mandrel with a shank was used. The mandrel, which weighed between 4.50 and 4.55 g, was composed of the alloy tool steel ХВГ.

The chemical composition of the alloy includes 1.2-1.6% tungsten, which enhances the wear resistance of the element. To achieve the necessary rigidity, the composition includes 1% of chromium and carbon, while 0.4% silicon increases its resistance to tempering, moreover, 1-2% manganese ensures structural integrity.

The mandrel drawings were made in the Compass 3D program, while the 3D models were constructed in SOLIDWORKS (*Figure 3*). 3D models were made in accordance with all the dimensions outlined by the mandrel drawings and correspond to full-scale mandrel models.

Two round supports, one at both the top and bottom composed of Ст3сп carbon steel, are needed to simulate the mandrelling process. The technical parameters of Ст3сп allow it to be used to produce the loaded elements of welded structures as well as machine parts and mechanisms that operate at high temperatures.

The pack consists of a sheet in which holes with a diameter of Ø5.8 mm are made, reamed and hardened by mandrelling. The sheet is made of the high-strength stainless steel 12Х18Н9Т (corrosion- and heat-resistant).

A good degree of resistance to atmospheric as well as intergranular corrosion combined with its heat resistance, stability, strength as well as ease of processing and use over a wide temperature range render this steel grade one of the most produced and applied in various industries, particularly in the manufacture of machine parts.

Simufact Forming is a full-featured end-to-end solution for simulating a wide range of metal forming technologies since it gives a realistic representation of technological operations with full 3D visualization of all tools and parts.

The program created a process called "Cold Forming" to which the mandrelling is referred. The parameter (option) "Setting" was selected and the type of calculation was 3D. The 3D models of all the necessary components created in SOLIDWORKS were transferred to the Simufact Forming software.

The previously transferred main geometric components of the mandrelling process with which the simulation was performed, namely the mandrel, the pack to be mandrelled as well as the top and bottom supports, are shown in *Figure 4*. The materials of all the transferred parts were also assigned.

To facilitate the calculations and reduce the computational complexity of the model, all the elements involved in the process were divided along the plane of symmetry. This method can be applied, since all the components in the mandrelling process are symmetrical.

A hydraulic press was used to push the mandrel. Transfer of the necessary force to the mandrel occurred with the help of a spring which was added to the top support. The initial state in which the spring for the hydraulic press was located was “compressed”. The direction of the spring action was from top to bottom. 90 J of work was applied to the mandrel. The press moved at a constant speed of 10 mm/s.

The frictional parameters between the 3D models were regarded as standards from the Simufact Forming software, that is, friction was combinational, the coefficient of friction was equal to μ=0.08 and the

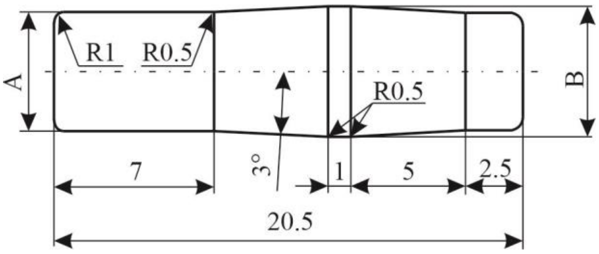

Figure 3. Dimensions of the mandrel
Diametrical dimensions of the inlet A and outlet B parts of the mandrel:
A1=5.57 mm, B1=6.10 mm
A2=5.63 mm, B2=6.16 mm
A3=5.70 mm, B3=6.18 mm

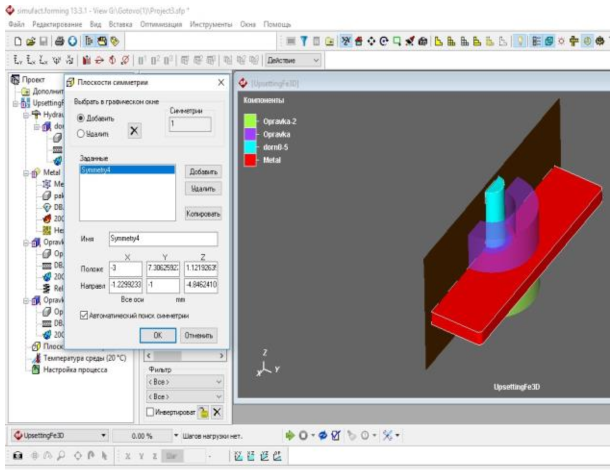

Figure 4. Transfer of the previously created geometry to the “Simufact Forming” software and splitting the symmetrical model

coefficient for modelling the wear process was equal to 1. The supports and mandrel were considered to be incompressible and elastic bodies, respectively. Since the deformation process is assumed to occur at cold temperatures, the room temperature, which was 20°C, was assumed to be the temperature of the plate and stamp. The heat transfer coefficient to the medium was assumed to be constant, namely 50 W/(m^2K).

The tension the mandrel was subjected to during the modelling of different holes was not equal but rather ranged from 0.25 to 5%. With such a tension, the pulling force was not excessive, moreover, during the mandrelling process, damaging cracks did not occur in the metal. The contact between the surfaces of the hole and mandrel was taken from the contact table in the software.

After adding and adjusting the geometrical parameters, two types of mesh were created; the first completely covered the mandrelled pack, while the second was created around the hole. The latter was somewhat larger than the diameter of the mandrelled hole and went slightly inside the hole. The structural resolution of the second mesh was better, which produced more accurate results from the calculation. This second mesh was in the form of a tube covering the

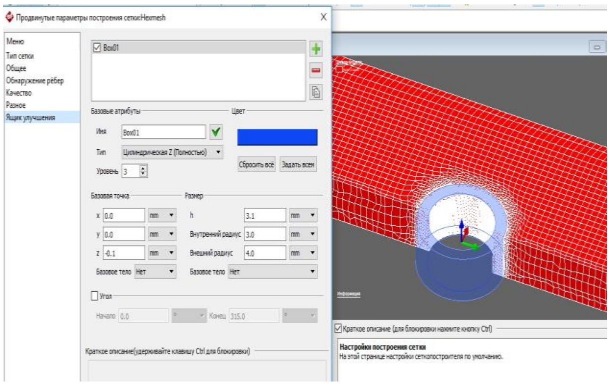

Figure 5. Creation of the second grid

required area around the hole, the vicinity of which was especially important for this study since plastic deformations and hardening of the walls of the holes took place. The dimensions of the mesh are as follows: height of 3.1 mm, inner radius of 3.0 mm and outer radius of 4.0 mm (*Figure 5*). By enhancing mesh refinement, more accurate simulation results can be obtained.

3.2. Simulations

The simulation results yielded data on the effective stresses along the hole and radial displacements that arise having been impacted by the mandrel. Before and after the mandrel was used as well as contact was made with the walls of the holes are presented in *Figure 6*. The distribution pattern of effective stresses in the vicinity of the walls of the holes is also visible. The stress scale on the left-hand side allows their values to be determined.

During the simulation, 3 points were selected: at the entrance to and exit from the hole as well as inside it. At these points, the diameters and radial displacements were measured. The same points were marked in all the experimental holes. The first one was marked at a depth of 0.5 cm from the entrance to the hole, the second in the middle of it and the third at a depth of 0.5 cm from the exit from the hole to avoid errors in the vicinity of where the corset was formed. The modelling process was carried out using five variations in the holes in the same sequence and by applying the same settings. Changes were only made to the geometry of the mandrel and to the hole pack.

The corset formed after the mandrelling process and metal deformation in the vicinity of the hole after hardening is presented in *Figure 7*. Radial movements in the vicinity of the hole indicate that its diameter slightly increased after mandrelling.

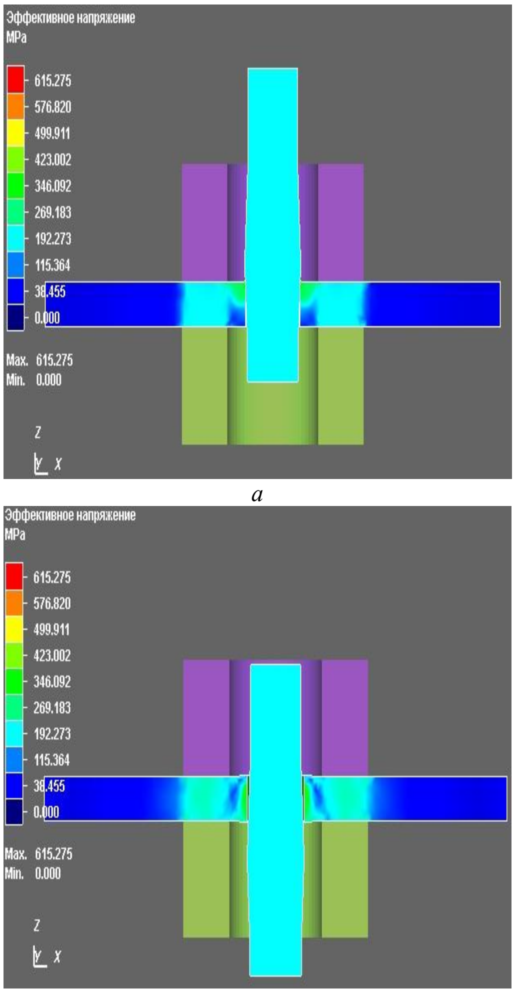

Figure 6. Starting point (*a*) and endpoint (*b*) of contact with the mandrel

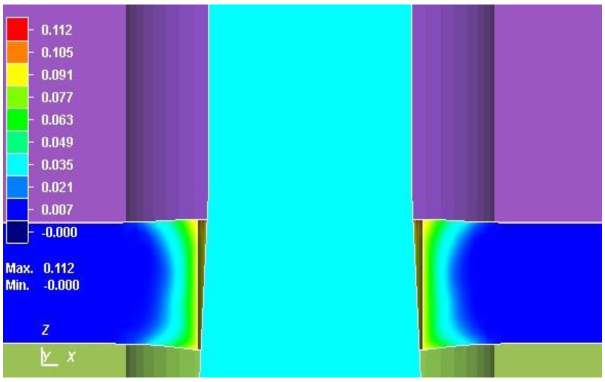

Figure 7. The appearance of sagging after hardening by the mandrel

4. Discussion

As a result, radial displacements in the holes after mandrelling were accurately measured as well as at the points selected after modelling at three different heights. The radial displacement data for all five variations in holes are recorded in *Table 1* from which the graphs shown in *Figure 8* were drawn.

The graphs and figures demonstrate the phenomenon of corset formation inside holes, preventing the walls of the holes from being perfectly cylindrical. This cannot be avoided by using a cutting tool since all the results obtained during hardening would be nullified by removing the mandrelled layer of the hole.

Table 1. Radial movement of the holes

No.	Initial diameter	Measuring points			Tension
		Top	Middle	Bottom	
1	5.92	6.102	6.088	6.102	3.0%
2	5.90	6.111	6.096	6.096	3.4%
3	5.80	6.110	6.089	6.096	5.0%
4	6.05	6.176	6.154	6.154	1.8%
5	6.17	6.184	6.171	6.177	0.25%

Part of the hardened material that was cut out of the hole creates an influx around its edge. A disadvantage of this phenomenon is surface distortion. Considering that several such holes can be located in certain areas and that bolted joints must fasten the "pack" together, difficulties, e.g. the formation of gaps between the plates, arise when they are stacked on top of each other.

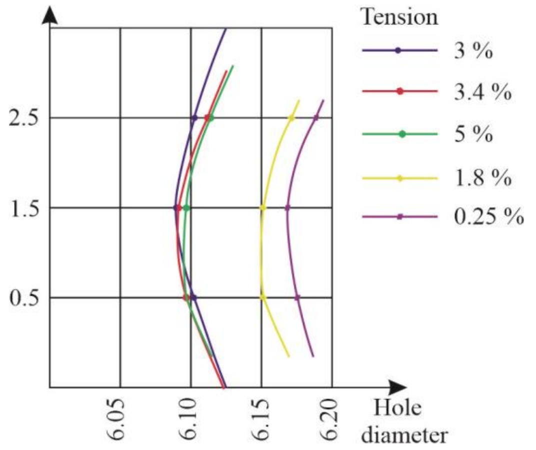

Figure 8. Change in radius data

5. Conclusions

Using the numerical model developed in the Simufact Forming program based on the finite element method, rational parameters of the technological process for impulse hole mandrelling in aircraft parts made of steel were determined for the first time.

At the end of the study, the following conclusions were made:

1. The developed numerical model of the technological process of impulse hole mandrelling in aircraft parts composed of steel enables rational parameters to be determined with a given degree of accuracy.

2. The rational parameters of the technological process of impulse hole mandrelling in aircraft parts composed of steel are determined as follows:

a) energy requirement of mandrelling is 90 J;
b) the angle α in the design of the mandrel must be equal to 3°;
c) the tension must fall within the range of 1.5-3.0%;
d) the coefficient of friction must be equal to μ=0.08, which corresponds to the use of lubricant type I20. (For the purpose of selecting the lubricant, an analysis of the literature and statistical data from studies on the effect of various types of oil when working with steel was carried out. The lubricant chosen ensured the sample was mandrelled under fluid friction, moreover, did not lead to molecular adhesion between the sample and tool.)

3. Simulation of the technological process made it possible to avoid the costs of expensive experimental studies.

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