Non-Cylindricity of Holes Formed with Robotic Complex

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Abstract. The article describes the technological features of the formation of holes with the help of the created robotic technological complex based on a Kuka robot. The robotic complex for machining allows you to drill holes in the Helmholz resonators to absorb noise in shells made of polymer composite materials (GFRP and CFRP) of aircraft engines. Holes for noise absorption with a diameter of 1.6–2 mm are required to be shaped in a significant array; 200-300 thousand holes must be drilled on one shell. The technological problems arising from the robotic drilling process are noted. One of the problems is the deviation from the cylindricity of the formed holes, the deviation arises due to the kinematics of the robot. A technical solution to this problem is proposed.

1. Introduction
The increasing competitiveness between companies requires means of production which meet an expected functionality at a reduced investment cost. This financial rationalization encourages industrial robotic to compete with machine as regards tasks for which the volume of the workspace is large and does not require a great accuracy up to 0.05 mm.

In 20 century the new class of constructional materials - polymeric composite materials (fiberglass and carbon fiber-reinforced plastic) has appeared which are widely applied in aircraft building, rocket production, shipbuilding. There are technological problems arising at machining polymeric composite materials [1, 2].

With the expanded use of polymer composites, we need to develop the corresponding theory and organize their production, with appropriate technology, equipment, and tools.

In cutting polymer composites, we should note the following features [2, 3]:

1) Delimitation of the polymer composite materials (as a rule, at points of tool exit) on account of the poor adhesion of the filler to the binder.
2) Difficulty in obtaining satisfactory surface roughness, on account of anisotropy of the properties. Individual selection of the cutting conditions and tool is required.
3) Low heat conduction of the material and correspondingly poor heat extraction from the cutting zone. (The tool absorbs 80–90% of the heat.)
4) Intense tool wear due to abrasion by the solid filler. Mechanical and hydrogen induced wear are also present.
5) Destruction of the polymer binder in cutting. Mechanical and thermal loads lead to chemical breakdown of the filler.
(6) Low productivity, on account of the low cutting rates. The use of lubricant and coolant fluid is limited, because the polymer composite materials absorbs moisture.

(7) Shrinkage on account of the elastic properties of the polymer composite. (The contact area is greater at the rear surface of the tool).

(8) Specific safety requirements, associated with the release of toxic volatile particles of material on cutting.

The literature largely lacks systematic information regarding the machining of polymer composites. The urgency of application of robots for machining polymeric composites in comparison to variants of application of machine tools explains to the following [4, 5]:
- Small forces of cutting, in comparison with processing metals, at drilling and milling of polymeric composites;
- The absence of large batches of let out products, that demands fast changeover the technological equipment;
- Occurrence of interfaces of control systems in robots at higher level, in comparison with machine tools. It allows to coordinate work of several components of the process equipment from the different manufacturers.
- Base cost robotic a complex is much less, than cost of multiaxis machines.

2. Project essence

2.1. Robotic complex

For today at robots the existing characteristic of accuracy of positioning repeatability 0,05 mm at repeating of 0,05 mm, and with the help of program calibration it is possible to achieve repeatability of 0,01 mm [5-13].

Existing problems of introduction of industrial robots for machining: difficult algorithm of programming, that demands the programmers mathematician of a high category.

Algorithm of programming robotic complex the following: creation 3D of model of object of processing a spelling of the managing programs in – CAM-SYSTEM for the processing centre, transformation of the managing programs for the processing centre in the managing programs for the robot. As it is visible, the circuit of programming robotic complex, as against the traditional processing centre, is longer on one step. Business in distinctions of degrees of freedom of the processing centre and robotic complex. The managing program is written initially independently for what - processing machine centre or robotic complex, and then for robotic complex exists special software adaptable the programs in the component programs for the robot.

For the sanction of industrial problems of manufacturing of sandwich construction, in view of technological features of processing polymer composites the tasks were put:
- Preliminary high-technology of a complex for machining products of the intricate geometrical detail form (5 axial processings) from polymeric composite materials;
  - Application of technologies for drilling (punching apertures) and milling;
  - Project of a technique of an estimation of integrity of the cutting tool during drilling (observation of breakages of drills of a small diameter at hit in partitions sandwich shells of polymer composites);
  - Research of questions of the machine control behind a trajectory of movement of working bodies and opportunity of updating of positioning of the tool at coordinate processing;
  - Creation of mathematical models of products as a cloud of points;
  - Rational components of a complex ensuring necessary kinematics of processes,
- Release equipment for fastening products;
- System design of algorithms of the managing programs;
- Selection of furnishing working bodies of a complex: high speed a spindle, tool, systems of ventilation, auxiliary components of the adaptive control.

In [4, 5], a robot created by the complex, allowing to carry out the perforation and milling operations in sandwich shells of polymer composite materials and the project is now implemented at JSC “Permsky zavod “Mashinostroitel“ (Perm Machine-building Factory).
After working through the complex technical solutions specification includes the following components of the robotic complex:
- industrial robots Kuka KR 60 HA, load capacity of 60 kg;
- dust sealed cover of the robot;
- the control panel to the controller;
- computer software package for working with CAM-files;
- high-speed servo spindle 8 kW with a maximum rotational speed of 24000 rev / min;
- positioner single-axis (rotary table) with a vertical axis of rotation, carrying capacity of not less than 500 kg;
- system scanning laser sensors tracking the path of the tool relative to the workpiece surface;
- control system zero point of the tool;
- a system of small-sized sensors tracking tool breakage;
- ventilation system with local suction and vacuum filtration unit;
- automatic tool changer magazine for ten instruments (replacement cartridges for the spindle, collet for various instruments (diameters of 2, 4, 6, 8, 10, 12, 16 mm), the tool;
- a device for securing the items;
- protecting fence and security locks with a mounting kit.
With the help of three-dimensional computer environment modeled robotic complex with all components and machined sandwich shell.

Robotic project of the complex is shown in Figure 1.

Figure 1. Model 3-D of robotic complex.

Dimensions and weight of processed parts: the diameter of 2500 mm; height of 1500 mm; Product weight up to 1000 kg.

The developed system allows to perform punching and milling in products such as sandwich shells.

Materials processed products: polymer composite, various non-metallic materials (plastic, wood, etc.).

The structure of the robotic complex includes active and passive safety systems, to prevent staff in the hazardous area of the industrial equipment.

The complex has a turntable (positioner KUKA KPF1-V500V2). The positioner works as an external axis of the complex. And as part of the robot-aided complex based KUKA robot, there are two options to connect the positioner).

2.2. Algorithm

The algorithm of the robot complex is as follows: creating a 3D model, then writing control programs in the CAM system for the processing center, converting control programs for the processing center into control programs for the robot. As can be seen from the above algorithm, the operation scheme of a robotic complex, unlike a traditional machining center, is one step longer. The difference is in the degrees of freedom of the machining center and the robotic complex.
The machining center has linear and circular axes, and in the robotic complex only the circular axes. Therefore, the control program is written initially independently for what - the processing center or the robotic complex, and then for the robotic complex there is a special software supplied together with the robotic complex to adapt the usual control program to the control programs for the robot with its rotational axes.

As the level of development of robotics rises, new opportunities for the use of robots in production constantly arise. With their help, now solve problems that were previously available only to expensive machines with numerical control. For new machining tasks, specialized software tools are being developed that improve the management efficiency and automation level of the preparation of control programs for robots. But if for machines with numerical control software there is a rich set of software systems that automate the creation of control programs, robot operators usually rely on manual step-by-step training, for which a special remote control is used. Autonomous development of control programs for the robot, also called off-line programming "Off-Line Programming" (OLP), offers a faster and more convenient way of defining the trajectories of the robot. Offline programming can be run on the computer at the same time as the robot continues to perform operations in accordance with the previously created control program. Only now have OLP-tools become available, the functionality of which allows you to take advantage of the significantly greater accuracy of modern robots. These tools have become software packages that provide the ability to generate manipulator movements based on CAD / CAM-system data.

2.3. Additional problems and solutions
When robotizing the formation of holes for absorbing noise Ø1.6 - 2 mm in sound-absorbing panels, the following problems occurred:
- To ensure the accuracy of the location of the holes - requires the consistency of the movements of the turntable with the installed workpiece blank and the movements of the robot with the spindle. In addition, the drill motion trajectory is different from the straight as shown in Figure 2 and Figure 3, so the accuracy of the hole.

![Figure 2. Input feed drill in an arc forms a noncylindrical](image-url)
In the robotic complex with the available six (6) degrees of freedom and, in addition, one more axis, due to the rotary table, they form a robotic complex with 7 degrees of freedom. However, even 7 degrees of freedom is not enough to perforate the holes to a depth of 20 mm strictly perpendicular to the curved inner surface of the shell. In fig. 2 shows the possible trajectory of the cutting tool in an arc. As a result of the implementation of such a trajectory during the formation of the holes, a deviation from cylindricity occurs, i.e. the real longitudinal section profile shifts from the shape of the ideal cylinder.

3. Equations and mathematics
When drilling holes in the Helmholtz silencers in the shells of aircraft engines, it is possible to deviate the profile of the longitudinal section of the cylindrical surface (non-cylindrical) due to the transfer of the drill axis, which is caused by:

1) Non-perpendicularity of the spindle axis of the robot to the plane of the shell to be machined;
2) The deformation of the technological system of the robot-spindle-tool-part.

The hole is a conditional cylindrical surface, and each cylinder is defined by the coordinates in Figure 4 of point A \((x_1, y_1, z_1)\) on the cylinder axis AB, the axis vector AB at angles \(\alpha, \beta, \gamma\), to the axes of ordinates, length AB and the radius \(r_1\) of the cylinder.
Consider the combination of movements in complex coordinate systems: from one to seven movements in a system with seven axes of coordinates. Let us analyze these combinations on translational displacements in the direction from the origin of coordinates; reversing movements double the number of combinations.

**One move.** The number of variants of permutations of one displacement in a system with up to seven axes of coordinates will be \( P=1 \), and this single displacement can occur along any one of the seven axes of coordinates. The number of placement options for one movement along the seven axes of coordinates is \( A_7^1 = 7 \).

**Six movements.** The number of variants of permutations of six movements in systems of up to seven axes of coordinates is \( P_6 = 720 \), and these movements are carried out in any of six of the seven axes of coordinates. Moves occur in a different order in the forward and reverse directions. The number of placement options of six movements in seven axes of coordinates \( A_7^6 = 5040 \).

**Seven movements.** The number of variants of permutations of seven movements in the system of seven axes of coordinates \( P_7 = 5040 \). The number of placement options is \( A_7^7 = 5040 \). Please note that \( A_7^7 = P_7 = 5040 \).

In Table 1 shows the possible combinations of permutation variants and arrangements of the moving nodes of the analyzed robotic complex. Not always selected layout is a rational technical solution.

**Table 1.** Summary of all possible permutations and arrangements along one to seven coordinate axes.

| The number of used axes | The number of permutations | Number of placements |
|-------------------------|----------------------------|----------------------|
| 1                       | 1                          | 7                    |
| 2                       | 2                          | 42                   |
| 3                       | 6                          | 210                  |
| 4                       | 24                         | 840                  |
| 5                       | 120                        | 2520                 |
| 6                       | 720                        | 5040                 |
| 7                       | 5040                       | 5040                 |

To realize the ideal shape of the hole in the longitudinal section in the form of a cylinder, it is necessary to use a drilling machine with automatic tool feed (DMAFT) on the robot flange instead of the well-known commercially produced spindle motors. Industrial examples of such machines are DMAFT firms Desoutter Seti-TEC (France) [14], Zephur (USA), Atlas Copco (Sweden), Recoules (France), etc. The production uses mainly two types of such machines, differing in the design implementation of the feed mechanism: with pneumatic cylinder and with a screw mechanism. To create smooth and low feed rates, some drilling machines are equipped with a hydraulic damper. However, drilling with such technological equipment is inefficient.

Therefore, it is required to create a light machine with the ability to quickly swap each new hole and with automatic and adaptive tool feeding. The domestic high-speed model DMAFT of this designation is located at PNRPU (Perm, Russia) in the development stage, with an adaptive feed: a decrease in the feed amount will occur at the end of the turn. Changing the axial feed when hit in the partition of the aggregate of the shell being processed also protect the drill from breakage. If there is an axial feed in the drilling machine, the hole will be cylindrical, that is, without deviations from cylindrical.

**4. Conclusions**

The creation of a new robotic complex for the mechanical processing of products made of polymer composite materials is a high-tech manufacturing platform. The proposed programming algorithm allows processing of a shell containing a multitude of points: 200 thousand and 300 thousand holes and more.
In order to avoid noncylidericity of holes when drilling on a robotic technological complex, it is necessary to improve the kinematics of the trajectory of insertion of the drill into the hole. The drilling machines with automatic feed can provide perfect kinematics of cutting tool insertion, such machines should be installed on the robot arm, and the mechanism of such machines can feed the cutting tool strictly perpendicular to the generator surface. In addition, with the use of such machines increases the reliability of the cutting tool.

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