The Problem Sensitization Robotic Complex Drilling and Milling of Sandwich Shells of Polymer Composites

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Abstract—**In clause is given robotic a complex for drilling and milling sandwich shells from polymeric composites. The machining of polymeric composite materials has technological problems. At drilling sandwich shells there is a probability of destruction of a drill from hit of the tool in a partition. The system sensibilization robotic complex for increase of reliability of work of the cutting tool of the small size is offered.**

Keywords: **Robot, Robotic Complex, Polymer Composite, Drilling, Milling, Sandwich Construction, Shell.**

I. Introduction

In all world it is known robotic complexes for manipulations of products, colouring, chemical processing, assembly-welding processes etc. In Russia robotic complexes on the basis of modern programmed robots having six degrees of freedom, for the decision of industrial tasks became distributed since 2003. The leaders among the manufacturers of robots for an industry were designated also: Kawasaki, Fanuc (Japan), Kuka (Germany), ABB (Sweden) etc. Till 2008-2010 years the application of robots for machining was exotic [1][2].

In 20 century the new class of constructional materials - polymeric composite materials has appeared which are widely applied in aircraft building, rocket production, shipbuilding. There are technological problems arising at machining polymeric composite materials [1][3][4].

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 [3][5]:

(1) Peeling and disintegration of the polymer composite (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 quality (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 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:

- 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.

II. Related Work

In whole all robots have anthropomorphic structure, geometrical similarity and technological similarity, and analog design [1][2][6].

On Fig. 1 shows the robots KUKA KR 60 HA, Kawasaki RS060N and ABB IRB 4600-60/2/05.

a) *b*) *c*)

Fig. 1. Robots:
a – KUKA KR 60 HA (Germany); *b* – Kawasaki RS060N (Japan); *c* – ABB IRB 4600-60/2/05 (Sweden)

Basic characteristics of robots - manipulators are given in Table1:

TABLE 1
CHARACTERISTICS OF ROBOTS-MANIPULATORS

Model		Kuka KR 60 HA		Kawasaki RS060N		ABB IRB 4600-60/2/05	
Country		Germany		Japan		Sweden	
Type		Articulated		Articulated		Articulated	
Number of axes		6		6		6	
Maximum reach, mm		2033		2100		2050	
Positioning repeatability, mm		±0,05		±0,07		±0,05-0,06	
Maximum total load, kg		60		50		60	
Range of motion software-limited		Range, °	Angular speed, radian/s	Range, °	Angular speed, radian/s	Range, °	Angular speed, radian/s
Number axis	Axis 1	±185°	2,23	±180°	3,14	±180°	3,05
	Axis 2	+35°, -135°	1,78	+140°, -105°	3,14	+150°, -90°	3,05
	Axis 3	+158°, -120°	2,23	+135°, -155°	3,22	+75°, -180°	3,05
	Axis 4	±350°	4,53	±360°	4,53	±400°	4,35
	Axis 5	±119°	4,27	±145°	4,53	+120°, -125°	4,35
	Axis 6	±350°	5,61	±360°	6,27	±400°	6,27
Maximum linear speed flange 6 axis, mm/s		No information		13400		No information	
Weight, kg		665		555		435	

For today at robots the existing characteristic of accuracy of positioning repeatability 0,05 mm at repeating of 0,05 mm (Table 1), and with the help of program calibration it is possible to achieve repeatability of 0,01 mm [7].

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 [2][6], 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»

After working through the complex technical solutions specification includes the following components of the 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 maxi mum 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 work piece surface;
- control system zero point of the tool;
- a system of small-sized sensors tracking tool breakage;
- ventilation system with local suction and vacuum filter SET Coy;
- 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 in Fig. 2.

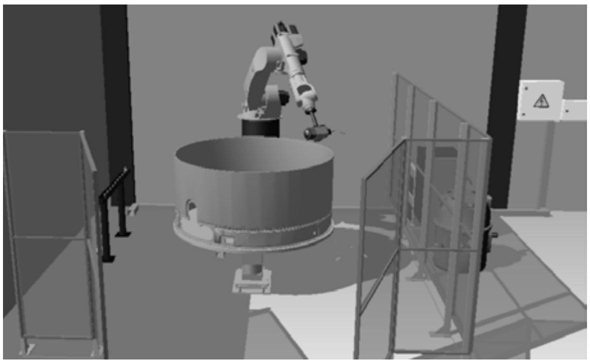


Fig. 2. Model 3-D of robotic complex

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:

- Asynchronous operation, thus, there is no mathematical connection with the robot;
- Mathematical connection with the kinematics of the robot.

An example of a mathematical relation is shown in Fig. 3.

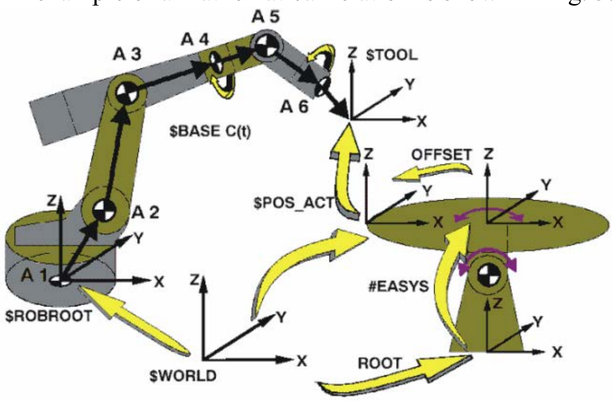


Fig. 3. Robot with external axes and extended kinematic system
Axes A1, A2, A3, A4, A5, A6 - mobile units. World coordinate system (World). Coordinate System tools (Tool). The coordinate system base (Base).

With connectivity options with a mathematical relationship, the drive continuously monitors the movement of the external axes. The mathematical relationship allows programming of complex processes.

Moving on each axis (Fig. 3), the robotic system can be a positive or negative direction.

When programming using three coordinates:

- Coordinate System World (World). Cartesian coordinate system with the on-roan reference at the base of the robot;
- Coordinate System tools (Tool). Cartesian coordinate system with the beginning of the report on the instrument;
- Coordinate System Base (Base). Cartesian coordinate system with coordinate basic origin report on the work piece.

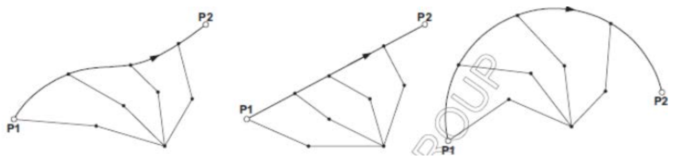
In practice, it is important that robotic system had been aligned in all three coordinate systems. Robotic system developed for the treatment of sandwich constructions connects and uses the base coordinate system and the coordinate system of the tool and for changing the cutting tool is used the world coordinate system (linking the base of the robot to the posts with the multipocket tool holder magazine for storage and tool change).

Another feature is the inclusion in the programming kind of movement of the robot, there are three:

a) Movement of the axes from point to point (PTP) (Fig. 4a). The tool moves on a fast path to the end point.

b) Motion for a linear path (LIN) (Fig. 4b). The tool is moved at a predetermined speed along a straight line.

c) Moving on a circular path (CIRC) (Fig. 4a). The tool moves with a given speed along a circular path.



a) b) c)

Fig. 4. Types of robot motion

Each of the three types of motion has submitted his interpolation speeds. All three motion graphics speeds leading axes of the robot consists of three phases: the phase of acceleration, constant phase, the phase of deceleration.

When choosing a software option (PTP) i. e from point to point, for each point on the path uses the maximum allowable speed.

When choosing a software option for linear motion tasks trajectory (LIN), the tool moves to the end point in a straight line while in motion on a trajectory is constantly changing from the initial position to the final orientation of the tool. This is achieved by turning and rotating the tool tip.

Similarly, when you select (CIRC) tool orientation in space is constantly changing from the initial position to the end.

When processing sandwich construction, namely, when drilling holes in sandwich construction possible breaking of the cutting tool of small size. The problem of prevention of tool breakage author dedicated to the work [8]. However, new technical solution to this problem is the implementation of sensitization, which is as follows.

Systems with proportional sensitization sensors allow automated processing drilling operation if it enters the walls of sandwich constructions. It requires dosing feed force based on an analysis of the situation in the zone of contact of the tool with the work piece. Consider a feature of such a system sensitization robot equipped with a force sensor, under the terms of technical operations necessary to adjust the feed rate of the tool.

When you install the force sensor in the collet tool in the drill tool coordinate system has three degrees of freedom, so the sensor measures the moments about the three axes.

Drilling cycle begins with the supply of drill holes to a coordinate axis of the sandwich construction, to achieve a set point efforts to drill axis X (in the coordinate system tools TOOL). Due to the partial entry into the drill hole when the drill hit in the partition there is some microscopic skewed relative to the axis of the drill holes allowed by the sensor elements. From the ratio of forces generated while the Y and Z, we can determine the actual presence of the partition. Instantly, the feed rate of the drill is to slow down and be included in the work routine that tapping on the drill coordinate this with the transition to the main program loop work piece.

This system solves the very difficult technological problem and can significantly improve the reliability of the cutting tool. The sensitivity of the system to errors in the orientation of the axes of the holes may increase when using the six-component force sensor, which measures the three components of force along the coordinate axes and three points with respect to these axes.

Analysis of the complete picture of the interaction of the power to evaluate terms of contact with the drilling operations of the sandwich construction, aimed to organize the search for a match axes of the holes and the walls and avoid tool breakage.

III. Mathematical Interpretation of Sensitization

An important sub-task in the system is the process of slowing down the robot drill feed, which is the use of so-called artificial compliance [9].

In the simplest case, when the interaction force F of the elastic sensor with the object, in this case, the isolating partition sandwich shell of the movement described by the equation of the second order

$$M\ddot{x} + k_4\dot{x} + F = k_3 U , \qquad (1)$$

where x – coordinate translational movement; M – the reduced mass of the moving parts of the robot; U – controlled by the signal applied to the actuator; k_4 – coefficient of friction in the system; k_3 – coefficient of amplification in the system control loop.

If we denote the coordinate of the point of contact of the sensor with an elastic wall sandwich construction and, if we neglect the mass of the sensor, in accordance with Hooke's law determine the force F

$$F = k(x - x_0) \text{ at } x \geq x_0 , \qquad (2)$$
$$F = 0 \qquad x \leq 0 .$$

The control law also assume a linear, such as

$$U = -k_1(F - F_{np}) - k_2\dot{x} ;\ k_1 > 0,\ k_2 > 0 , \qquad (3)$$

where F_{np} – software enhancement of interaction of the sensor with the object formed by the control system of the robot; k_1, k_2 – coefficient of amplification.

Force F_{np} corresponds to a certain program coordinates defining the expression $x_{np} \geq x_0$, defined by the expression (2), i.e $F_{np} = k(x_{np} - x_0)$.

Thus, to create some control loop, which is not regulated by the position of the final level, and some effort to link the robot interaction with the environment. Indeed, the equation (1) with (2) and (3) can be transformed to the following vat:

$$M\ddot{x} + (k_4 + k_3k_2)\dot{x} + k_3k_1k(x_0 - x_{np}) = 0$$

provided $x \leq x_0$, (4)

$$M\ddot{x} + (k_4 + k_3k_2)\dot{x} + k(x - x_0) + k_3k_1k(x - x_{np}) = 0$$

provided $x \geq x_0$. (5)

The term in $k_3k_1k(x_0 - x_{np})$ в (4) shows that $F_{np} > 0$ and $x \leq x_0$ the system operates in a constant force proportional F_{np}. This means that the position of the hand, wherein the sensor probe is not in contact with the sandwich construction, is variable, and the link will move in a direction determined by the signs of the coefficients in (3). After reaching the contact with the sandwich construction in the drill begins elastic interaction with the treated surface of the work piece past the sensor probe in Step drilling layers (in the equation (5) is expressed in terms) $k(x - x_0)$).

Interaction is to achieve a predetermined force, if the partition will meet, and the full stroke of the drill into the work piece, if the partition is encountered. This corresponds to the normal action of a mechanical spring (sensor hardness) and "programmable" spring (in the equation (5) shown by the term $k_3k_1k(x - x_{np})$, of equivalent mechanical rigidity k_3k_1k).

Thus, the linear feedback force affects the movement unit in the same way as a conventional mechanical spring. The advantage of this spring is the ability to program control its stiffness by changing the ratio k_1. Those, when modifying the sandwich construction (thickness variation, variation in strength and other characteristics of the material) required minimum time for changeover robotic system.

In the position of static balance is provided by a constant force F in contact equal $k_3 k_1 F_{np} / (1 + k_3 k_1)$.

The effect on the power of the drive servo system obtained based on the expressions (4) and (5) solves the problem of the sensitivity of the drive actuator - when spindle motion robotic complex that is necessary for the operations of machining of sandwich constructions. This feature allows you to set sensitizing robotic drilling walls and stiffening ribs of sandwich constructions made of polymer composite materials without sudden breakage of the cutting tool when need to dispense feed force of the cutting tool along the axis of the drill during drilling. In addition, the sensitivity of complex robotic prevent possible deformation of the sandwich constructions during milling.

IV. Conclusion

It showed a robotic system for drilling and milling sandwich constructions made of polymer composites. The main feature of the complex is developed that solves the proposed robotic complex technological problems arising in the processing of articles made of polymeric composites. When drilling sandwich constructions there is a risk of damage of the cutting tool in contact with the tool in the partition. The proposed system is complex robotic sensitization increases operational reliability of the cutting tool for small size. Sensing robot can protect the sandwich structure from undesirable deformation during milling windows, grooves or elements.

By development of tracking systems on force for robotic complex, it is necessary also to consider stability of all system at detailed elaboration of dynamic model, oscillatory processes and other effects of a control system. But it is themes of separate researches.

As the level of development of a robotics raises, constantly there are new opportunities of application of robots in manufacture. The specialized software are developed for new tasks of machining which raise a management efficiency and level of automation of preparation of the managing programs for robots.

In Russian Federation of analogues created robotic complex is not present. The basic foreign alternative variant is the system LASERDYNE SYSTEMS of the company PRIMA North America, Inc. (USA) used by corporation Boeing [1].

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