Roughness of holes in metal and polymer composite bags

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Abstract. The article presents the results of the research on the influence of cutting modes on the parameters of surface roughness during finishing of holes in mixed packages containing composite and metal materials. The object of the study is a mixed package containing layers of polymer composite material (CFRP), as well as layers of titanium and aluminum alloys. The main technological equipment used in the study is an automatic drilling machine. Cutting tool - carbide six-toothed reamer. For carrying out of researches ranges of variation of modes of cutting have been chosen and the plan of experiment by means of software Statistica 6 is made. Two factors are considered under the plan of experiment: speed of cutting and delivery, the parameter of the allowance on expansion is introduced as the block factor. The models of multifactor dispersion analysis, which determine the influence of modes on the roughness of holes, were obtained empirically. Optimization of cutting modes has been carried out, the surface of desirability has been constructed, and recommendations on the choice of technological parameters of the process have been given.

Key words. Unfolding, unwrapping, mixed bag, carbon fiber.

1. Introduction

In modern mechanical engineering, the question of the need to reduce the weight of the product while maintaining high parameters of strength [1, 2] is acute. The most promising directions for solving this problem are the use of composite materials [3, 4]. Carbon plastics have a combination of high strength and elasticity, not inherent in metal materials [5-7]. In some cases, the use of only one material does not provide the required strength, in such cases, a combination of two or more materials connected to each other either by a glue layer or a fastening joint [8, 9]. These material compounds are called mixed bags [10].

The greatest difficulty lies in the formation of holes for fastening joints in mixed bags containing heterogeneous materials [11], which have opposite requirements to the processing modes [12]. So for packages containing layers of titanium alloys and composite materials the cutting modes satisfying the requirements of each of the processed materials are in rather narrow boundaries, [13, 14]. Therefore, it is necessary to determine the dependence of the hole roughness on the selected modes for each layer [15, 16]. In such cases, it is effective to apply the technique of experiment planning, which provides the determination of the minimum number of cycles of hole processing necessary to determine the optimal cutting modes [17, 18]. Reduction of the number of cycles is relevant for studies using a blade tool, with increasing cycles of which wear increases, which affects the quality of data obtained [19].

The presented research is primarily designed to apply its results in the assembly of the promising
MS-21 aircraft, including the processing of holes in the joint "wing-centroplan". The main feature of which is the so-called "black" wing made of modern composite materials. Figure 1 shows the scheme of distribution of materials in the design of the glider.

![Material distribution diagram in the airframe structure](image)

**Figure 1.** Material distribution diagram in the airframe structure

### 2. Experiment

**Object of research, cutting tool and research methodology**

The object of research is a 5-layer mixed package "OT4 (titanium alloy) - BT6 (titanium alloy) - CFRP (carbon fiber) - BT6 (titanium alloy) - 1933 (aluminum alloy)).

Figure 2 shows the sketch of the mixed bag with the thickness and direction of processing.
Figure 2. Sample sketch for testing.

The main tool is a six-toothed reamer manufactured by Mapal with channels for the supply of cooling lubricant (MQL) [20].

For experiments, a pneumatic drilling machine with automatic tool feed was used Atlas Copco PFD-1500.

Roughness measurement was performed by a contact method on a Taylor Hobson profiler using a 2 μm radius diamond tip probe. This measurement method does not involve sample failure. The roughness was determined in each layer separately. The length of the scan route is 80% of the thickness of the measured layer. A parameter characterizing the hole roughness is the parameter Ra.

3. Statistical analysis
In this study, the factors of variation were the cutting speed and feed rate. The values of the levels in natural and normalized form are presented in the table 1.

| Table 1. Natural and normalized levels of plan factors |
|-----------------------------------------------|
| Factor         | Level -1 | Level 0 | Level 1 |
| Cutting speed, m/min (Speed) | 6.1      | 11.8    | 17.5    |
| Delivery, mm/turn (Feed)      | 0.16     | 0.27    | 0.38    |

As a block factor the allowance for deployment on diameter of openings was considered. Values of allowances are given in table 2.

| Table 2. Natural and normalized levels of the plan’s block factor |
|---------------------------------------------------------------|
| Block            | Level 1 | Level 2 |
| Allowance for unfolding, mm (Block) | 0.1      | 0.5     |

The design of the experiment was carried out using the Statistica software. The module of the central compositional plan was not full-factor, which allowed to estimate the dependences without testing on all modes. Thus, it was possible to minimize the impact of tool wear on the obtained data [21, 22].

Table 3 presents the matrix of the compositional plan.
Table 3. Matrix of the central compositional plan

| № of the experiment | Allowance for unfolding (block factor), X | Cutting speed, m/min | Delivery, mm/turn |
|---------------------|-----------------------------------------|----------------------|-------------------|
| 1                   | 1                                       | -1                   | -1                |
| 2                   | 2                                       | -1                   | 0                 |
| 3                   | 2                                       | 0                    | 0                 |
| 4                   | 2                                       | 1                    | 0                 |
| 5                   | 1                                       | -1                   | -1                |
| 6                   | 2                                       | 0                    | 1                 |
| 7                   | 2                                       | 0                    | -1                |
| 8                   | 2                                       | 0                    | -1                |
| 9                   | 1                                       | 0                    | 0                 |
| 10                  | 2                                       | 0                    | 1                 |
| 11                  | 2                                       | 0                    | -1                |
| 12                  | 1                                       | -1                   | -1                |
| 13                  | 2                                       | 0                    | 1                 |
| 14                  | 1                                       | 0                    | 0                 |
| 15                  | 1                                       | 1                    | 1                 |
| 16                  | 2                                       | 1                    | 0                 |
| 17                  | 1                                       | 1                    | -1                |
| 18                  | 1                                       | 0                    | 0                 |
| 19                  | 1                                       | -1                   | 1                 |
| 20                  | 1                                       | 1                    | 1                 |
| 21                  | 2                                       | -1                   | 0                 |
| 22                  | 1                                       | -1                   | 1                 |
| 23                  | 1                                       | 1                    | 1                 |
| 24                  | 1                                       | -1                   | 1                 |
| 25                  | 1                                       | 1                    | -1                |
| 26                  | 2                                       | 0                    | 0                 |
| 27                  | 2                                       | -1                   | 0                 |
| 28                  | 2                                       | 0                    | 0                 |
| 29                  | 1                                       | -1                   | -1                |
| 30                  | 2                                       | 1                    | 0                 |

4. Results

1. Titanium alloy layer OT4

Using regression analysis, we determined that the determination coefficient is $R^2=0.45$ and found regression coefficients. As a result, we got a regression model

$$Ra_{OT4}=1.05+0.05\text{Block}+0.08\text{Speed}+0.16\text{Speed}^2+0.06\text{Feed}+0.01\text{Feed}^2+0.09\text{Speed}^*\text{Feed} \quad (1)$$

The analysis of the model has shown the following, that in this case the block factor of the allowance for deployment has an insignificant impact on the roughness, so it is enough to build a response surface for one allowance (Figure 3).
Changing the roughness parameters with increasing cutting speed is parabolic in nature. The feed rate influences the roughness according to the linear law. The minimum roughness value corresponds to the average cutting speed. Deterioration of roughness parameters corresponds to low and high cutting speeds.

2. First layer of titanium alloy Vt6
In this case, the determination coefficient was $R^2=0.79$. After determining the regression coefficients, the model for the Vt6 became as:

$$Ra_{Vt6_1}=0.76-0.06\text{Block}+0.01\text{Speed}-0.11\text{Speed}^2+0.12\text{Feed}-0.02\text{Feed}^2+0.05\text{Speed}^*\text{Feed}$$  \hfill (2)

From the obtained model it follows that the block factor influences the roughness parameters, so it is necessary to consider the response surfaces for each seam allowance (figure 4, 5).

Figure 3. Response surface of Ra parameter from cutting modes for OT4 layer (allowance 0.1 mm).

Figure 4. Response surface of Ra parameter from cutting modes for Vt6_1 layer (allowance 0.1 mm).
Figure 5. Response surface of Ra parameter from cutting modes for Vt6_1 layer (allowance 0.5 mm).

Average cutting speeds correspond to the worst roughness parameters, with low and high cutting speeds providing minimum values. Increasing the allowance has a positive effect on the resulting roughness.

3. Layer CFRP (CFRP)

Determination coefficient in PCM layer $R^2=0.34$. The resulting model for the PCM layer looks like:

$$Ra_{CFRP}=1.28+0.11\text{Block}-0.01\text{Speed}+0.12\text{Speed}^2+0.12\text{Feed}+0.08\text{Feed}^2+0.01\text{Speed}^2\text{Feed} \quad (3)$$

The block factor has a significant impact on the surface profile (figure 6, 7).

Figure 6. Response surface of Ra parameter from cutting modes for PCM layer (allowance 0.1 mm).
Figure 7. Response surface of Ra parameter from cutting modes for PCM layer (allowance 0.5 mm).

For the PCM layer, it was found that the change in cutting speed affects the quality to a much lower degree than the feed rate. The minimum roughness corresponds to a low feed rate and average cutting speed. Increasing the feed rate reduces the roughness of the machined surface.

4. The second layer of titanium alloy Vt6
In the Vt6 layer, the determination coefficient R²=0.81. The obtained model for the Vt6 layer looks like:

\[ Ra_{Vt6_2} = 0.81 - 0.02 \text{Block} + 0.03 \text{Speed} - 0.11 \text{Speed}^2 + 0.13 \text{Feed} - 0.01 \text{Feed}^2 + 0.04 \text{Speed} \times \text{Feed} \]  \hspace{1cm} (5)

The roughness in the Vt6_2 layer is less affected by the allowance than for the Vt6_1 layer. Otherwise, profiles for both layers have a similar structure (Figure 8).

Figure 8. Response surface of Ra parameter from cutting modes for Vt6_2 layer (allowance 0.1 mm)

Having considered the obtained surface, we come to the conclusion that the change in the feed rate practically does not affect the roughness, when the increase in the cutting speed leads to its deterioration.

5. Aluminum alloy layer 1933
Determination coefficient for layer 1933 R²=0.76. The resulting model for the aluminum alloy layer looks like:
\[ Ra_{Al} = 1.39 - 0.04 \text{Block} + 0.23 \text{Speed} - 0.53 \text{Speed}^2 + 0.27 \text{Feed} + 0.19 \text{Feed}^2 + 0.18 \text{Speed} \times \text{Feed} \]  \hspace{1cm} (5)

In this case, the block factor of the allowance for deployment does not have a significant impact on the roughness response profile, so it is enough to build a response surface for one allowance (Figure 9).

![Image](image1.png)

**Figure 9.** Response surface of Ra parameter from cutting modes for aluminum alloy layer (allowance 0.1 mm)

In an aluminium alloy layer, the roughness response profile has a maximum at medium cutting speeds and a minimum at low and high speeds.

5. **Optimization of cutting modes**

With the help of the Statistica 6 software package the conditions for the most preferable roughness parameters were set. Having built the desirable surface and determined the optimal cutting modes that provide maximum performance and low roughness (figure 10).

![Image](image2.png)

**Figure 10.** Graph of desirability
The analysis of the obtained surface showed that the best roughness is provided on the cutting modes corresponding to the average cutting speed of 11.8 m/min and the minimum feed rate of 0.16 mm/revolution. It is expedient to increase the productivity with minimal influence on the roughness parameters by increasing the feed rate up to 0.38 mm/rpm and maintaining the cutting speed at the level of 11.8 m/min.

6. Conclusion
1. The models of multifactor regression analysis for each layer of five-component mixed package OT4-BT6-CFRP-BT6-1933 are obtained. The models determine the effect of cutting modes on the surface roughness of holes. Introduction of the received models gives the chance to define the optimum modes of cutting providing reduction of machine time and increase of quality of processing.
2. Technological parameters of the cutting process, such as cutting speed, feed rate and allowance for deployment, have a significant impact on the surface roughness of the machined holes. Their effect on each layer of the mixed package is individual.
3. Defined cutting modes combining high quality of holes and machining capacity: cutting speed 11.8 m/min and feed rate 0.38 mm/rpm.

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