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Comparison of qualimetric indexes of winding and laying-up at profiled composite parts manufacturing

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An analysis of the qualimetric indicators of the winding and laying processes used for the manufacture of profiled long parts of aircraft from composites was carried out. A single curvature panel was selected as a typical part that can be manufactured using manual laying or automated winding processes.

The assessment of the duration of typical technological processes for the manufacture of a representative part includes considering both the main and auxiliary technological processes of preparation and direct production. A profiled long part of a square cross-section was selected to include the pultrusion process in the comparison. Using the analysis of modern literary sources, the influence of such a characteristic of technological processes as the complexity of a part on the characteristics of its quality was separately investigated. A method for numerically evaluating the quality indicators of technological processes for the production of composite profiles was proposed. Also, the material utilization factor is used when comparing manufacturing processes. This method involves the use of the method of expert assessments that use the weighting factors of the influence of each technological process.

The goal of research is to develop an engineering methodology for comparing complex quality indicators of technological processes with the subsequent selection of the most effective process with the development of relevant recommendations.

The subject of research is the quality indicators of the technological processes of automated winding, manual laying and pultrusion.

Methods used in the research. The study used the method of qualimetric analysis of the indicators of the technological processes of manufacturing panels of single curvature and profiled products from composites.

Recommendations have been developed for taking into account such most significant properties of production processes and parts that are manufactured as the complexity and strength of the product, the cost of production equipment, process productivity and qualification of workers, which should be taken into account when analyzing quality indicators.

Key words: qualimetric analysis, winding, laying-up, composites, manufacturability, quality.

Introduction

Winding, layup, and, less commonly, pultrusion processes are most often used in the manufacture of profiled parts from composite materials (CM). Profiled parts typically include heavily loaded spars, beams, stringers, and various fittings, which are subject to complex stress-strain conditions during aerospace operations. Strict weight requirements and the high cost of reinforcing and adhesive materials require a denser fiber distribution per cross-sectional unit of the material and strict adherence to the structure (reinforcement angles) specified by the designer. The combination of thermal loading during material formation and the desired CM structure causes warping of parts during manufacturing and subsequent assembly. This physical phenomenon must be considered when choosing a particular forming process.

The wide range of capabilities of the fore mentioned processes – namely, direct, spiral, and combined winding, manual and automated layup, and a combination of pultrusion and spiral winding – require comparison for various purposes. A comprehensive assessment can be conducted using qualimetric analysis.

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Review of previous studies

In extensive papers on the technology of manufacturing parts of polymeric materials [1, 2, 3], a comparison of the technical and economic indexes of several typical wide spread technological processes is presented. This comparison is carried out using the example of the production of a single-curvature panel, which can be used as aircraft skin, a car body part, and other transport equipment (Table 1).

By analyzing these values, we can draw the following conclusions [4-6]:

1. The index values are presented on a 10-point scale, which is not entirely suitable for calculating qualimetric indicators. However, these values can easily be converted into relative unit quality indexes (QIs). Their maximizing and minimizing nature should be considered.

2. The proposed list of indexes lacks a rather important one – the coefficient of material usage (CMU). CMU values can be easily estimated by examining the formation mechanism of a part – in this case, the profiled part.

3. The large difference in productivity estimates between manual laying and winding (3 times) raises some doubts. Machine time for winding and manual laying should be calculated using known relationships [1-5]. By examining the process sequence in detail, the relative labor intensity of these two processes for manufacturing a profiled part can be estimated.

Table 1

Technical and economic assessment of production methods for reinforced plastic products by 10 score points scale

Processes	Part Complexity	Part Strength	Cost of tooling	Production volume	Qualification of operator
Hand lay-up	9-10	3	1	2	10
Winding	4	10	6	6	2
Pultrusion	2	10	7	9	2

Labor intensity of winding. For winding of profiled parts with a complex reinforcing material structure, it is rational to use the spiral (oblique) winding method, the schematic diagram of which is shown in Fig. 1.

This design allows control of the winding angle and the combination of spirally arranged layers of reinforcing material with longitudinal or transverse fibers. It enables the winding of round, square, rectangular, and other convex-shaped products with relatively smooth radii at the edges.

Considering the mechanism of filling the surface of a mandrel with tape, it is easy to calculate the duration T_{layer} of filling the surface of the mandrel with one layer of reinforcing material:

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$$T_{layer} = \frac{\Pi}{V_{in}} \frac{L_{sp}}{b}, \tag{1}$$

where Π – mandrel section perimeter; V_{in} – the rate of reinforcing tape income to a mandrel surface; L_{sp} – semi-finished part length; *b* – width of reinforcing tape.

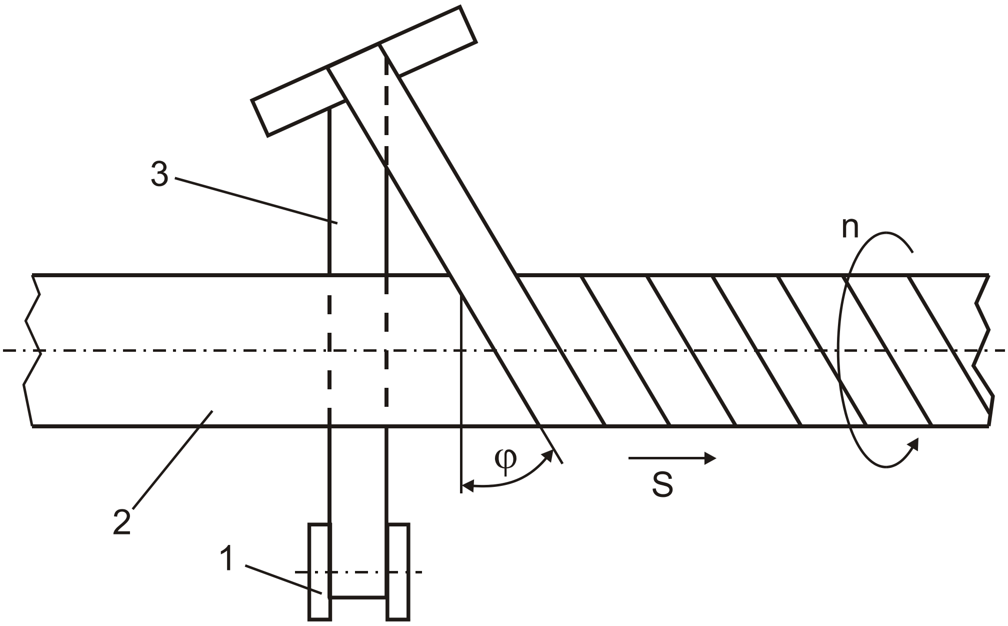

Fig. 1. Scheme of spiral winding: 1 – bobbin with tape;
2 – mandrel; 3 – winding tape

The controlled technological parameter in this dependence is the rate V_{in}. Recommendations for selecting its values lie in a fairly wide range – from 0.24 [1] to 18 m/min for some types of winding machines [3]. The practice of winding cylindrical cylinders [6] leads to the conclusion that higher speed values should be considered in the calculations, up to values at which drops of binder begin to break off from the “wet” wound surface of the mandrel under the action of centrifugal forces.

The second important technological parameter is determining the required mandrel length (or blank length). Analysis of the reinforcing material placement pattern reveals that there are separate sections with an irregular layer filling structure at the initial and final ends of the mandrel. The length of such sections is determined by the perimeter of the mandrel, the fiber reinforcement angle, the width of the reinforcing tape, and (in case of layers overlap) also by the overlap size. Required length of winding semi-finished part L_{sp} with regular reinforcing angle can be calculated as following:

$$L_{sp} = L_{part} + 2\Pi tg\varphi + \frac{b}{cos\,\varphi} + L_a, \tag{2}$$

where L_{part} – part length; φ – tape reinforcing angle; L_a – length of allowances.

In this formula, the second and third terms determine the length (on both sides) of irregular sections, while allowances are necessary to secure the initial sections of

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the wound tape, which can accumulate additional binder squeezed out by the laid turns of tape, as well as other defects due to process imperfections. The length of allowances is usually taken as 5-10% of the total length of the part for both sides of the mandrel.

An analysis of this relationship shows that spiral winding of short parts with a large cross-sectional perimeter is less efficient than for long parts. When manufacturing short parts, it is necessary to combine the winding of several parts on a single mandrel. This ensures higher CMU values.

When winding profiled parts with significant changes in cross-sectional perimeter along the part's length (end sections of spars and ribs, stringers, and beams with variable cross-sections), it is necessary to reduce the perimeter (mass) of the material fed into the winding (reinforcing material and binder). Feeding material to areas with smaller cross-sectional perimeters from larger perimeters leads to the formation of folds and bulges [7, 8].

In this case, using a combination of winding and laying out monolayers reduces the likelihood of these shape and structure distortions. Laying out monolayers of the appropriate structure can compensate for the reduction in cross-sectional perimeter. For profile parts with a decreasing perimeter along the longitudinal axis, it is recommended to control the feed rate of the wound material and the layer stacking step.

To estimate the labor intensity (productivity) of winding and laying out, let us consider an example of manufacturing a square profile with a side of 50 mm and length of 1 m. The width of winding tape is 10 mm, reinforcing angle is 45°. Calculated length of semi-finishes product L_{sp} (2):

$$L_{sp} = 1.0 + 2 \cdot 0.2 \cdot 1.0 + \frac{0.1}{0.71} \approx 1.4\ m.$$

Technological time T_t for creation of a single layer of composite can be found as following:

– for V_{in}=1 m/min T_t=0.2$\cdot\frac{1.4}{0.01}$=28 min, revolution speed is 7.6 rev/min;

– for V_{in}=10 m/min T_t=2.8 min, revolution speed is 76 rev/min.

Technological time for winding of 20 layers is 56 min, auxiliary time (appr. 10 %) is 5.6 min. Total duration is 61.5 min.

The rate of winding is selected as average from the range 0.24…18 m/min. This ensures relatively quiet and stable winding conditions without significant influence of inertial forces.

Labor intensity of laying-up process. To compare processes by parameter of labor-intensity of parts manufacturing one can consider labor-intensity of analogous part with square cross-section and side dimension of 50 mm, lenth of 1.0 m and wall thickness 2.0 mm. The part consists of 20 layers of reinforcing material with thickness of 0.1 mm and reinforcing angle 45°.

Predicted length of a semi-finished part is 1.1 m. Technological time T_1 for laying-up on smooth surface of a single layer with area S=0.5·11=5.5 dm^2 can be found by following formula [5]

$$T_1 = \frac{-B + \sqrt{B^2 + 4 \times A \times S}}{2A},$$

where A=4.2·10^{-2}; B=4.5 – empirical coefficients.

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Duration of a single layer laying-up on a single mandrel surface is 1.21 min, duration of four surfaces laying-up is 4.84 min, duration of 20 layers laying-up is 96.8 min.

Auxiliary time which is spent for enveloping ribs of a mandrel and layers overlapping or butt joining, checking-up and layers rolling down is approximately equal to 1.5…2.5 times from the time for direct laying-up and assumed to be equal to 144.8 min. Therefore, labor intensity of laying-up overexceeds the winding duration in ~2.35 times even at manufacturing of relatively simple article by geometry.

Indexes of this comparison are very close to ones shown in the Table 1, exactly: 2.35 and 3.0 for profiled article and panel with single curvature correspondingly.

Let's compare other process parameters. The laying-up process requires a tooling consisting of a smooth mandrel and four surface jig. The mandrel is virtually identical in design to the winding mandrel. Manufacturing jigs from sheet material requires minimal labor intensity, and they are reused multiple times. Therefore, the transfer of their manufacturing labor intensity to the labor intensity of the part is negligible.

CMU during winding is slightly higher than that during laying-up. During laying-up, the length of the workpiece, including trimming allowances, is 10% of the length.

When winding a longitudinal part, the allowance for trimming an irregular structure and the distortion of the part's wall thickness depends on the winding angle, the perimeter of the cross-section profile, and the tape width (see formula (2)) and, in the calculation, amounted to 40% of the part's length.

Based on literature sources it is possible to assume that CMU for laying-up is 0.9 and for winding is 0.55…0.75. To increase it, it is rational to combine two or more parts on one tool.

Let's compare the qualimetric parameters of the winding and layup processes. It should be noted that in a qualimetric analysis, it is advisable to consider 5-7 of the most influential process parameters. This analysis must consider the feasibility of implementing a given reinforcement scheme, the volumetric content of the composite, and their degree of tension.

Based on these considerations source [1, 7, 8] develops a preferred sequence for selecting manufacturing processes for parts: automated winding, pultrusion (can be combined with winding), manual layup (preferably mechanized), and spraying.

To calculate for the technical and economic indexes of processes for a part manufacturing author provides Table 1 with a few such indexes, presented on a 10-point scale. These values can easily be converted to relative quality indexes [6], but at the same time considering their maximizing or minimizing nature, and also replacing the 10-point assessment with a 9-point one for simplicity of calculation (Table 2).

Table 2

Selected quality indexes K_i for several typical manufacturing processes for articles made of reinforced plastics (calculated using data shown in the Table 1) [1-3]

Process	Part complexity	Part strength	Cost of equipment	Labor intensity*	Operator qualification	CMU**
Hand lay-up	0.9	0.3	0.9	0.2	0.1	0.95
Winding	0.4	0.9	0.4	0.6	0.8	0.65
Pultrusion	0.2	0.9	0.3	0.9	0.8	–

* The values of winding and laying-up productivity calculated by the author differ

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by only 1.7 times for the considered part.

**Average values for a square profiled section with reinforcement angle calculated by the author.

A comprehensive quality index that considers the key process characteristics, as a first approximation, as the arithmetic mean of individual property indexes in their considered environment. The weight of each individual property is determined by a weight coefficient (Table 3).

Corresponded values of indexes K_i and g_i are shown in Table 4. Sub-index "i" relates to the list of manufacturing processes.

Table 3

Expert estimation of unit indexes value g_i for profiled composite parts manufacturing processes

Indexes	Part complexity	Part strength	Cost of equipment	Labor intensity*	Operator qualification	CUM
Expert 1	0.8	0.9	0.4	0.3	0.6	0.5
Expert 2	0.3	0.9	0.5	0.5	0.4	0.3
Expert 3	0.7	0.8	0.4	0.4	0.6	0.7
Average value	0.6	0.87	0.43	0.4	0.53	0.5

Table 4

Values of indexes product ($K_i \cdot g_i$) for different manufacturing processes

Process	Part complexity	Part strength	Cost of equipment	Labor intensity*	Operator qualification	CUM**
Hand lay-up	0.54	0.26	0.39	0.08	0.05	0.48
Winding	0.24	0.78	0.17	0.24	0.42	0.32
Pultrusion	0.12	0.78	0.13	0.36	0.42	–

* Values of manufacturability for winding and laying-up calculated by author differ only in 1.7 times for considered part.

** Average values calculated for square section with reinforcing angle selected by author.

The value of complex index of quality K^{compl} can be estimated by the following formula [8-10]:

$$K^{compl} = \sum_{i=1}^{n} \frac{g_i \cdot K_i}{n},$$

where g_i и K_i – unit weight indexes and quality indexes of corresponding manufacturing processes.

Results of analysis of complex quality index for processes of manufacturing panels with single curvature and profiled parts made of composites show following results:

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– for hand laying-up K_{hl}^{compl}=0.30;

– for winding K_{w}^{compl}=0.36;

– for pultruzion K_{p}^{compl}=6.68.

Conclusions

Analysis of these values of K^{compl} and ones shown in Table 4 allows to conclude that the property of "part complexity" relates mostly to general characteristic of part forming, nevertheless paper [1, 8] declares it for forming of single-curvature panel. Generally, geometry of panels can be complicated, with different local elements and smooth with low curvature. In this case, the analysis examines the molding process of profile parts, which, in their product range, have a completely different, simple shape, but are extended along a single axis. Therefore, as a preliminary assumption, the property of "part complexity" can be excluded from consideration. All other properties, to a first approximation, are important for analyzing the manufacturing processes of profile parts.

After the appropriate calculations, we obtain:

– for hand laying-up K_{hl}^{compl}=0,25;

– for winding K_{w}^{compl}=0,39;

– for pultrusion K_{p}^{compl}=0,42.

Thus, a quality analysis of the production of profile parts in two variants reveals the following process sequence, arranged in descending order of the overall quality indicator: pultrusion, winding, and manual layup. This sequence is largely determined by the productivity of the processes. The above calculation of the machine time for winding and layup confirms the higher productivity of the pultrusion process.

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Порівняння кваліметричних показників процесів намотування та викладки профільних деталей з композитів

Проведено аналіз кваліметричних показників процесів намотування та викладення, що використовуються для виготовлення профільних довгомірних деталей літальних апаратів з композитів. У якості типових деталей, які можуть виготовлятися за допомогою технологічних процесів ручного викладування або автоматизованим намотуванням обрано панель одинарної кривизни.

Оцінка тривалості типових технологічних процесів виготовлення представницької деталі включає врахування як основних та і допоміжних технологічних процесів підготовки та проведення безпосереднього виробництва. Для включення до порівняння також процесу пултрузії обрано профільована довгомірна деталь квадратного перерізу. За допомогою аналізу сучасних літературних джерел окремо досліджено вплив такої характеристики технологічних процесів як складність деталі на характеристику її якості. Запропоновано методику числового оцінювання показників якості технологічних процесів виробництва композитних профілів. Також при порівняння процесів виготовлення використовується коефіцієнт використання матеріалу. Ця методика передбачає залучання методу експертних оцінок, які використовують вагові коефіцієнти впливу кожного технологічного процесу.

Метою дослідження є розробка інженерної методики порівняння комплексних показників якості технологічних процесів з подальшим вибором найбільш ефективного процесу за розробки відповідних рекомендацій.

Предметом дослідження є показники якості технологічних процесів автоматизованого намотування, ручної викладки та пултрузії.

Методи, що використані у дослідженні. У дослідженні використано метод кваліметричного аналізу показників технологічних процесів виготовлення

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панелей одинарної кривизни та профільованих виробів з композитів.

Розроблено рекомендації щодо урахування таких найбільш вагомих властивостей процесів виробництва і деталей, що й виготовляються, як складність і міцність виробу, вартість виробничого устаткування, продуктивність процесу й кваліфікація робітників, які слід ураховувати при аналізі показників якості.

Ключові слова: кваліметричний аналіз, намотування, викладення, композити, технологічність, якість.

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