Evaluation construction made of polymer composite materials by molding using reusable flexible punches production profitability

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Abstracts. One of the most common methods for the production of composites is the vacuum infusion method, which consists in the use of a disposable flexible punch pressed to the surface of the mold by atmospheric pressure. A new technology is the use of reusable flexible punches also pressed by atmospheric pressure. The paper compares the profitability of the same construction by these methods production.

1. Introduction
Using vacuum infusion technology, a wide range of products can be manufactured. So, with this technology it is possible to produce both small products – car bumpers, helmets, and very large ones – aircraft wings, ship hulls [1]. The largest product size is limited only by the size of the workshop in which the production is located.

The essence of the technology is that the layers of the future product are laid in a sealed vacuum bag, from which air is subsequently removed by a vacuum pump and impregnated with a polymer binder [2]. Creating a vacuum inside the bag allows the use of atmospheric pressure as a press. By pressing the bag to the product surface, the layers of the reinforcing filler are compressed, which leads to an increase in the mechanical characteristics of the composite by reducing the amount of binder [3].

To carry out the impregnation of the product, a conducting mesh made of polymeric materials having volumetric weaving is laid, which creates a vacuum between the reinforcing filler and the bag. Due to the fact that the conducting mesh laid on reinforcement layers can become part of the future product, it is separated by a sacrificial layer, also known as Peel Ply. In addition, to install the package requires a sealing harness, ensuring the tightness of the vacuum bag. The sequence of laying the layers used to implement the vacuum infusion technology is shown in Fig. 1.
Figure 1. Layering procedure in infusion technology: 1 – mold; 2, 5 – sealing tape; 3 – sealant agent; 4 – filler layer, 6 – peel ply, 7 – conducting mesh, 8 – vacuum film, 9 – pneumatic valve

Due to the nature of the technology, this method can produce constructions whose thickness does not exceed 15-20 mm. In other words, infusion is excellent for creating shell structures, while it is almost not applicable for thick-walled parts.

Vacuum infusion allows for relatively small financial costs to produce constructions with high surface quality and a more controlled percentage of binder in the composite in comparison with contact molding. A great advantage of the technology is also a low pore content compared to contact molding [4]. But first of all, the content of pores depends on the preparation of the binder immediately before molding. It is worth paying attention to the fact that for the implementation of infusion technology, a conventional rotary vane vacuum pump and a trap for a binder are sufficient. The cost of the pump, as a rule, is low in comparison with the equipment used to implement other technologies, such as presses, autoclaves, component accessories, etc.

The main disadvantage of infusion can be considered a large number of used technological materials that are disposed of after a single use. These materials include: peel ply, conducting mesh, sealing tape, vacuum and spiral tubes, as well as the vacuum film itself. Such a large number of purely technological materials significantly increases the cost of products manufactured by infusion technology in medium-series production. It is most successfully used in single or small batch production [5].

As a technology that allows you to take advantage of both vacuum infusion and press technology, you can use technology with a reusable flexible punch [6]. With their help, it is possible to produce composite products based on both thermoplastic and thermoplastic matrices [7]. Fig. 2 shows the design of the stand with a reusable flexible punch. This equipment also includes a vacuum system that cannot be shown in this figure.
Figure 2. Equipment with a reusable flexible punch: 1 – a countertop; 2 – a pressure cover with a punch; 3 – a control panel; 4 – a heating element (a block of infrared lamps)

In relation to composites, molding technology using such equipment can be classified as small-scale or single. This is due, first of all, to the fact that the bulk of the time, as well as in infusion technology, is occupied by the manual laying out of the layers of the future composite for tooling, preparation of a binder, impregnation, etc. The main difference from the traditional method of infusion is the use of a reusable flexible punch that acts as a vacuum bag, and the lack of the need to search for air leaks from under the sealing tow [8].

These features can reduce the complexity and time consumption compared to traditional molding methods, and the convenience of layout (pump, degasser and vacuum traps are located directly under the countertop) to reduce the size of the working space due to the fact that molds and material can be laid directly on the countertop, which is rather important both for industrial and engineering companies [9].

2. Objects and methods
A skateboard was chosen as a product for comparing the two technologies (Fig. 3). This product is suitable for molding both with vacuum infusion technology and with the silicone punch.

Figure 3. Skateboard
Mold of the product was designed in an Autodesk Inventor (Fig. 4) and was milled on a CNC machine from an MDF board 30 mm thick (Fig. 5). This material was chosen due to its low cost and ease of machining.

![Skateboard mold model](image1)

**Figure 4.** Skateboard mold model

![Skateboard mold](image2)

**Figure 5.** Skateboard mold

Due to the fact that the mold material, as a whole, is a product of wood processing, it has a high porosity and surface roughness. When composites are molded, the surface of the product repeats the surface of the tooling, including microroughnesses, scratches, and other similar defects, which in the case of MDF can significantly reduce the quality of the product. In addition, these defects increase the level of adhesion, which, due to the low strength of MDF, leads to its destruction after several moldings. To increase durability, you need to get a glossy mold surface. This was achieved by surface treatment with Sealer Mikon 399MC pore-filling compound applied evenly on two-layer mold. This composition creates a thin solid polymer film, which is then easily processed by hand or mechanical grinding tools.

### 3. Results and Discussion

The production time of a typical construction for engineering company [10] was chosen as an indicator of the technologies effectiveness under consideration. The laying scheme is shown in Fig. 6.
Figure 6. Layout of reinforcing and technological layers for the skateboard manufacture: 1 – carbon fabric; 2 – SORIC nonwoven fabric; 3 – peel ply; 4 – conducting mesh; 5 – vacuum film (silicone punch)

To compare the time spent, 3 moldings were made using each of the technologies described above. The time was measured by an independent expert using a stopwatch. The molder worked at the usual, measured pace. The average time of each of the stages of production is presented in table 1. Not taken into account the time spent on connecting the tubes to the vacuum pump, as well as cutting and cutting tissue due to their insignificance.

Table 1.
Comparison of production time using infusion technology and a reusable punch

| Infusion                  | Silicon punch          | Average stage time (min) |
|---------------------------|------------------------|--------------------------|
| Reinforcing Layers        |                        | 40                       |
| Laying peel ply           |                        | 5                        |
| Laying conducting mesh    |                        | 5                        |
| Installation of spiral and vacuum tubes for supplying a binder and pumping air | Installation of spiral tubes for supplying a binder and pumping air | 7 |
| Bonding of sealing tape   | –                      | 10                       |
| Vacuum bag installation   | –                      | 20                       |
| Vacuum bag compression    | –                      | 8                        |
| Vacuum bag leak repair    | –                      | 10                       |
| Total time: 105           | Total time: 57         |

After this, impregnation and curing is performed under an infrared lamp for 1 hour [11, 12]. Removing the product from the mold takes 10 minutes.

As practice has shown, the time for forming a single product using a silicone punch is 33% faster than by infusion technology. Obviously, with an increase in the number of layers, the percentage will decrease, since the difference in technology is only the installation of the package and the sealing harness for it [13].

It should also be noted that due to the absence in the technology of disposable vacuum bags, usually made of polyethylene, polypropylene or nylon, the amount of garbage in production is reduced. This, in turn, helps to increase the environmental friendliness of production.
The calculation of the cost of materials necessary for the production of one product using vacuum infusion technology is presented in table 2. As a currency, conventional units are used, reduced to the cost of real materials.

**Table 2.**
Calculation of the cost of materials required for vacuum infusion

| Material                  | Cost per square meter or meter of material, units | Number of layers | Area, m² | Cost, units |
|---------------------------|---------------------------------------------------|------------------|----------|------------|
| Carbon fabric             | 160                                               | 5                | 0,2      | 160        |
| SORIC nonwoven fabric     | 82                                                | 1                | 0,2      | 16.4       |
| Peel ply                  | 25                                                | 1                | 0,2      | 5          |
| Conducting mesh           | 18                                                | 1                | 0,2      | 3.6        |
| Vacuum film               | 8                                                 | 1                | 1        | 8          |
| Sealing tape              | 3.5                                               | 1                | 2.8      | 10         |
| **Total**                 | **203**                                           |                  |          |            |

Since the price of a product made using a silicone punch does not include a vacuum bag and a sealing tape, therefore, it will amount to 185 units.

Considering that the working day at the production site is 8 hours, find the theoretical number of manufactured products per day. Accept that one person with one equipment works on the site. Since in the calculation obtain non-integer values of the quantities of units per day, to approximate the conditions of real life, round them down (Table 3).

**Table 3.**
Calculation of the productivity of infusion technologies and reusable punch

|                      | By infusion technology, min | By reusable punch technology, min |
|----------------------|----------------------------|----------------------------------|
| Molding              | 105                        | 57                               |
| Curing               | 60                         | 60                               |
| Product retrieval    | 10                         | 10                               |
| Total time           | 175                        | 127                              |
| Working hours        |                            | 480                              |
| Pieces per day       | 2                          | 3                                |

With this production method, each of the actions of the molder is sequential, that is, after molding, curing follows, in which, the worker is not engaged in production activities or rests. To increase the productivity of the worker, it makes sense to make a second mold. In this case, the molder is able to lay out the fabric in parallel with the curing process of the product in a polymerization furnace. It is worth noting that the existing vacuum-membrane press has dimensions that can accommodate only one product on its countertop. When using more dimensional installations, accordingly, it is possible to further increase the number of products manufactured in one cycle.

To compare labor productivity during molding using two rigs, both during molding using a membrane press and the method of vacuum infusion, Gantt charts were constructed (Fig. 7, 8). The numbers on the diagram indicate the processes of product forming.
As can be seen from the above charts, the productivity when working with a reusable punch is 6 products per day, and during infusion – 3 products per day. It is worth noting that despite the fact that the last product produced per day does not have enough time for curing in the oven, curing can occur at room temperature in the absence of a worker using automatic shutdown equipment. Therefore, it makes sense to consider that the infusion rate is 4 pieces per day.

It should be noted that due to the fact that the vacuum punch becomes unusable over time, the cost of changing it is also worth considering. The average cost of one linear meter of a punch with a thickness of 3 millimeters and a maximum elongation of 600% is 795 units. Since the length of the table is 1.3 meters, the cost of the punch for the existing vacuum press will be $m = 1033.5$ units. According to the manufacturer, the punch is able to withstand $t = 300-500$ molding cycles. Take this value equal to $t = 400$.

Knowing the labor productivity $p_i$ for both technologies, it is possible to find the number of manufactured products per month. Assume that in the month $d = 21$ working days.

$$n_i = p_i \cdot d \quad (1)$$

For infusion:

$$n_{inf} = p_{inf} \cdot d = 4 \cdot 21 = 84 \text{ pieces per month}; \quad (1.1)$$
For reusable punch:

\[ n_{RM} = p_{RM} \cdot d = 6 \cdot 21 = 126 \text{ pieces per month}; \]  

(1.2)

Take the worker’s salary equal to 300 rubles per hour, therefore, for a month his salary will be:

\[ z = 21 \cdot 8 \cdot 300 = 5040 \text{ units}. \]  

(2)

The cost of buying a new punch will be per month:

\[ M = m \cdot \frac{n_{RM}}{\tau} = 1033.5 \cdot \frac{126}{400} = 325.5 \text{ units}. \]  

(3)

Since the cost of materials for production is 203 units for infusion technology and 185 units for a silicon punch, the total cost of materials per month will be:

for infusion:

\[ T_{inf} = 2030 \cdot n_{inf} = 203 \cdot 84 = 17052 \text{ units}; \]  

(4.1)

for reusable punch:

\[ T_{RM} = 185 \cdot n_{RM} + M = 185 \cdot 126 + 325.5 = 23635.5 \text{ units}; \]  

(4.2)

Total costs include both the cost of materials and the salary of the worker:

for infusion:

\[ S_{inf} = T_{inf} + z = 17052 + 5040 = 22092 \text{ units}; \]  

(5.1)

for reusable punch:

\[ S_{RM} = T_{RM} + z = 23635.5 + 5040 = 28675.5 \text{ units}; \]  

(5.2)

The resulting income is calculated as 1.3 of the cost of production:

for infusion:

\[ D_{inf} = 1.3 \cdot 22092 = 26510.4 \text{ units}; \]  

(6.1)

for reusable punch:

\[ D_{RM} = 1.3 \cdot 28675.5 = 34410.6 \text{ units}. \]  

(6.2)

Consequently, profits from sales of skateboards will amount to:

for infusion:

\[ P_{inf} = D_{inf} - S_{inf} = 26510.4 - 22092 = 4418.4 \text{ units}; \]  

(7.1)

for reusable punch:

\[ P_{RM} = D_{RM} - S_{RM} = 34410.6 - 28675.5 = 5735.1 \text{ units}. \]  

(7.2)

Since the profit is made from the sale of all skateboards produced in a month, the cost of one of them will be:

for infusion:

\[ I_{inf} = \frac{D_{inf}}{n_{inf}} = \frac{26510.4}{84} = 315.6 \text{ units}; \]  

(8.1)

for reusable punch:

\[ I_{RM} = \frac{D_{RM}}{n_{RM}} = \frac{34410.6}{126} = 273.1 \text{ units}. \]  

(8.2)

Thanks to the use of new technology, it is possible to reduce the final cost of the product by
Since the profit on the new technology is higher by

\[ P_{RM} - P_{inf} = 5735.1 - 4418.4 = 1316.7 \text{ units per month}; \]  \hspace{1cm} (10)

All results of economic calculations are presented in table 4.

| Economic calculation results | Infusion | Reusable punch |
|-------------------------------|----------|----------------|
| Number of pieces per day      | 4        | 6              |
| Pieces per month              | 84       | 126            |
| Cost of materials             | 203      | 185            |
| Cost of punch                 | -        | 1033.5         |
| The number of molds that the punch can withstand | - | 400 |
| Worker’s salary               |          | 5040           |
| Monthly Costs                 | 22092    | 28675.5        |
| Monthly income                | 26510.4  | 34410.6        |
| Profit                        | 4418.4   | 5735.1         |
| The cost of one skateboard    | 315.6    | 273.1          |

4. Conclusion

The presented technology can be used to replace vacuum infusion technology without compromising product quality. Due to the vacuum bag installation process optimization, the production time of one product is reduced, and, as a result, the productivity of the method increases. At the same time, the cost of the product is reduced by 14%.

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