Self-Heating Mould for Composite Manufacturing

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The shipbuilding industry, engine manufacturing, aviation, rocket and space technology are promising fields of application for polymeric composite materials. Shape-generating moulding tools with internal heating are used for the creation of a more economically viable method of moulding of internally heated composite structures. The use of a fine-fibered resistive structure in the heated tools allows implementation of effective heating of the composite and elimination of the need for expensive and energy-intensive heating equipment.

Keywords: resistive element ; internal heating ; exothermic effect ; heating system power ; laying pitch ; thermal blanket

1. Introduction

At the present time, composite materials based on ultrathin carbon, glass, organic and other types of fibres in combination with polymeric binders are widely used in various branches of technology[1][2][3][4], such as general construction, bridge engineering, road infrastructure, transport, agricultural machinery, the power sector, biomedicine, and petro-chemistry[5][6][7][9][8][10]. The shipbuilding industry, engine manufacturing, aviation, rocket and space technology are the most promising fields of application of polymeric composite materials[11][12]. High specific strength and stiffness, as well as a number of other unique properties of the composites, which allow the implementation of special qualities in the structure, are in demand in these fields[13][14].

One of the most rational methods of repair of typical operational defects (cracks, penetration defects of skin, delaminations) in metal and composite panel constructions is the installation of patches made of polymeric composite materials[16][15]. The high physical and mechanical properties of the composites and the significant advantages of the adhesive joints over mechanical ones, determine the successful use of patches made of polymeric composite materials for the repair of both polymeric and metal structures of various applications[17][18][19]. Because the need for repair of structures in the future will continue to grow, increase in the efficiency of repair processes is no less important than improvement of the methods of designing of new structures[20][21][22].

Moulding of products of polymeric composite materials is performed, as a rule, with the use of heaters (furnaces or autoclaves). The efficiency of any heating method is determined by the ratio of produced and transferred heat, therefore the introduction of contact heaters in the manufacturing of composites is an urgent task [23][24]. It allows reduction of the time and costs for the production of composite structures. Now there are several areas in the development of heating equipment, which provide reduced energy consumption in the process of creation and reconditioning repair of composite structures. In order to implement new methods of composite structure moulding, binder compositions cured by ultraviolet radiation or another type of radiation have been developed, as well as heating complexes where the shaping surface of the tools is an integrated part [25]. However, such complexes are characterized, apart from high cost, by the great complexity of production, operation, and maintenance; therefore, they do not find wide industrial application.

For the creation of a more economically viable method for moulding of composite structures, heated moulding tools are developed, to which the heat is supplied by convective or contact heat transfer. The use of resistive blocks in the heated tools allows implementation of efficient heating of the polymeric composite materials without significant changes to the tool design [26]. The heating units can be manufactured on the basis of the fine-fibered resistive structure or plates/small cores. The main disadvantage of plates and units with a core is the gap occurring in the process of unit installation; the resulting temperature difference can be compensated only by a sufficient thickness of the shaping surface of the tool. Resistive blocks based on fine-fibered resistive structures are the only units, which allow implementation of the uniformity of the temperature field on the shaping surface, when the resistive blocks are installed with a gap equal to the pitch of the laying of the resistive thread [27].

Authors of the paper[28] propose a cure of the binder by applying an electric current to the carbon fibre composite part. It was shown that the electrical conductivity of carbon fibre allows individual fibres to act as heating elements. As a result, there is a large number of internal heating elements throughout the composite part. The degree of curing was compared to composites cured in the traditional way. The three-point bending test was used to determine the flexural strength and modulus of elasticity. The results showed that the proposed technology provided polymeric composite material parameters on a level with autoclave production.

A method of direct resistive heating of the composite workpiece for curing was proposed in[29]. The heat problem was solved numerically by the finite element method. In this case, the heat conduction equation and kinetics of the binder curing reaction in the composite workpiece were modelled. Since the resistivity of materials is temperature dependent, a system with nonlinear relationship was developed. Comparison of the obtained results with experimental data showed satisfactory repeatability.

The paper[30] deals with the study of the method of self-resistive electric heating for the rapid moulding of parts of carbon fibre reinforced plastic. For the generation of heat and direct curing of the bind

er, the use of the electric current passing through the carbon fibre was proposed. A self-resistive tool with an automatic temperature controller was developed. This study presents the results of experiments on the moulding of composite parts with the use of the developed equipment. The degree of curing of various specimens was characterized, and their cross-sectional geometry and porosity evaluated. On the basis of the experimental results, the behaviour of the heat transfer of various processes was analysed.

To reduce the autoclave costs, the use of a self-heating composite mould made of carbon fibre composite was proposed in . It was suggested to use the reinforced carbon fibre composite shaping surface as the heating elements. The paper shows that due to the very low coefficient of thermal expansion of carbon fibre composite, this material is an excellent choice for the manufacturing of such moulds. The predicted uniformity of the temperature field was confirmed experimentally using thermocouples and an infrared camera.

A self-heating composite tool with built-in resistive layer was developed in[31][32] . It was shown that this layer evenly distributes the heat in close proximity to the surfaces of the part while ensuring a high level of mechanical characteristics of the polymeric composite materials. Finite element modelling of heat transfer confirmed that the tool configuration and selected heating elements provide sufficient heat uniformity to achieve the desired binder curing. Nevertheless, the paper indicates the necessity to solve the problem of choosing the optimal position of the resistive layer, as well as further testing to verify and calibrate the system to obtain the the optimal degree of binder curing.

The method for calculation of the heated tools providing rigidity and service life, with the heating layer based on the resistive blocks, was proposed in[33]. The parameters of the heating system (material of the heating elements, their geometry, and material of the insulating system) and the diagram of its connection were determined from the condition of securing the required heating mode. The heating was controlled by changing the current strength during the process, determined from the solution of the heat conduction problem, taking into account the exothermic effect of the curing reaction and conditions of heat transfer on the surface.

The thermodynamic model of unsteady heat transfer during moulding of the polymeric composite material in heated tools was developed in[34]. The model allowed the temperature distribution over the thickness of the system under study to be obtained, the influence of the exothermic effect of the binder curing reaction to be evaluated, and the required power of the heating system to be determined. The disadvantage of this paper is the assumption that the model does not take into account the ribbing of the lower surface of the moulding tools.

As shown from the review and analysis of the problem, the possibility of out-of-autoclave production of the composite parts with the use of moulding tools with internal heating has now been substantiated. It eliminates the need for the expensive and energy-intensive heating equipment. For the improvement of the preproduction activity through a reasonable choice of the design of the moulding tools, it is necessary to develop an integrated solution, which allows reducing costs and shortening the production cycle. Therefore, the aim of the paper was to reduce energy consumption for internally heated moulding tools by choosing the optimal parameters of the resistive layer.

To achieve this purpose, it was necessary to solve the tasks below:

2. Numerical Implementation

Numerical validation of the developed method was carried out on an example of moulding equipment for the formation of package based on fiberglass and Hysol EA 9396 binder, where the amount of heat ΔH = 400 kJ is released in the process of curing of one kilogram of the binder.

Figure 5 shows the dependence of the required power of the resistive layer on the time required for maintenance of the given temperature–time regime on the lower surface of a moulded package of 2 mm thickness, as well as the distribution of the temperatures on the outer surfaces of the manufactured package of the polymeric composite material.

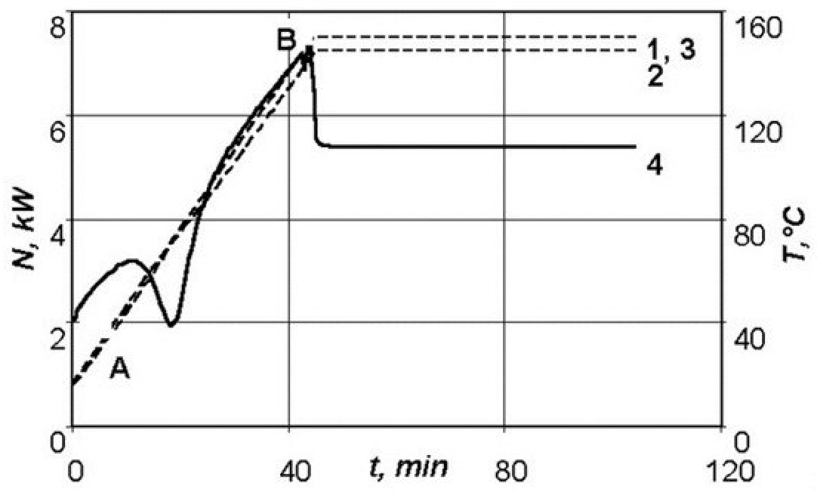

Figure 5. Dependences of parameters of the standard conditions of moulding of a package of 2 mm thick: 1—temperature versus time on the lower surface of the product; 2—temperature versus time on the upper surface of the product; 3—temperature versus time for the theoretical conditions; 4—power versus time.

As can be seen in **Figure 5**, the sharp drop in the required power in section AB is explained by the exothermic effect of the curing reaction of the Hysol EA 9396 binder. As a result of self-heating of the system, the required power of the resistive layer noticeably drops in the time interval from 10 to 25 min, after which the graph of dependency of the required power on time becomes linear. The jump at point B is explained by the transition from the heating stage to the holding stage, at which the supplied energy is consumed only for the compensation of the convective heat transfer from outer surfaces of the thermodynamic system. An insignificant jump in temperature on the upper surface of the moulded package corresponding to the area of the required power dropping is explained by the fact that the presented thermodynamic system allows control of the temperature on one surface of the moulded product only. As previously determined, the choice of the lower surface as the control will prevent overheating of the structure on the upper layers of the moulded package, so that a higher quality product can be obtained.

Figure 6 shows the temperature–time relationship on the outer surfaces of the moulded product for a similar thermodynamic system, when the thickness of the moulded package is 5 mm, as well as the dependence of the required power of the heating system on time. In this case, the power of the resistive layer drops to zero at point B, which is explained by the growing exothermic effect of the curing reaction with the increase in thickness of the moulded package. **Figure 6** shows that in section BC the exothermic effect of the curing reaction cannot be compensated only by convective heat removal from the outer surfaces of the system, and leads to the temperature peak on the lower surface of the moulded product at the heating section.

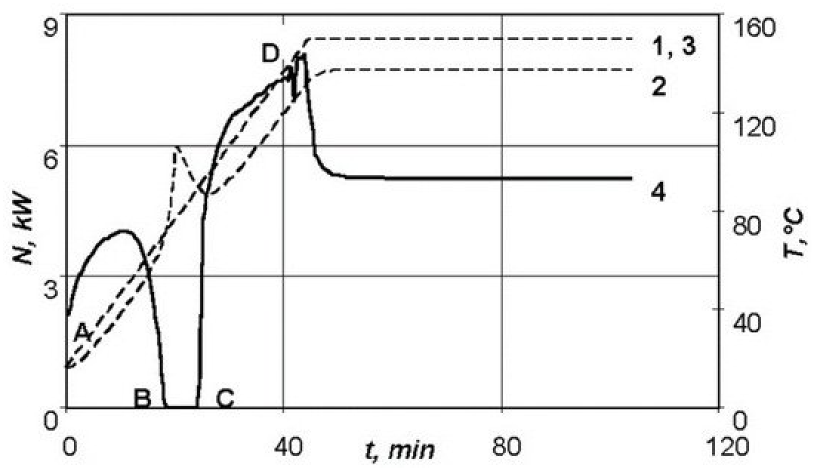

Figure 6. Dependences of parameters of the standard conditions of moulding of a package of 5 mm thick: 1—temperature versus time on the lower surface of the product; 2—temperature versus time on the upper surface of the product; 3—temperature versus time for the theoretical conditions; 4—power versus time.

Therefore, the specified temperature–time regime for a product with such a thickness cannot be implemented using this equipment. Since large temperature gradients can lead to significant technological stresses, it is advisable to revise the conditions of moulding of the manufactured part, and possibly replace the binder used by another one, without such a pronounced exothermic effect.

The values of the required power, as well as the energy consumption for different heating rates of the thermodynamic system are presented in **Table 1**. It can be seen that the heat effect of the reaction growswith the increase in the heating rate of the product, and at a heating rate of 8 °C/min the power of the resistive layer drops to zero. Thus, variation of the rate of temperature rise in the moulded product is an effective way to control the power of the polymerization reaction exothermic effect.

Table 1. Required power and energy consumption values for different heating rates.

Heating Rate, °C/min	Required Power of Resistive Layer, kW	Energy Consumption, kW/h
1	6.15	7.16
2	6.78	4.17
3	7.51	3.18
4	8.10	2.68
5	8.78	2.38
6	9.46	2.19
7	10.15	2.04
8	10.83	1.94

The material of the moulding tool also has a significant effect on the amount of consumed energy and the nature of its consumption. The values of the required power and energy consumption for various materials of the shaping surface of the tool when its thickness is changed are given in **Table 2**.

Table 2. Required power and energy consumption values for the heating system of moulding tool when the thickness of lower part of the shaping surface is changed.

Thickness of Lower Part of the Shaping Surface, mm	Required Power of the Heating System, kW	Energy Consumption, kW/h	Required Power of the Heating System, kW	Energy Consumption, kW/h	Required Power of the Heating System, kW	Energy Consumption, kW/h
	Fiberglass		Aluminium Alloy		Steel	
0.5	6.99	2.81	7.06	2.83	7.20	2.90
1	7.16	2.94	7.37	2.97	7.46	3.12
2	7.51	3.18	7.71	3.27	8.16	3.57
4	8.08	3.62	8.49	3.86	9.91	4.45
6	8.56	4.01	9.44	4.45	10.53	5.34
8	8.96	4.33	10.35	5.04	12.18	6.22
10	9.44	4.60	11.44	5.62	12.87	7.10

For example, for the fiberglass moulding tool, the power value gradually increases, excluding the area which balances the exothermic effect, while the metal tool is characterized by initially high energy consumption, associated with a high heat capacity ratio of the shaping surface material. The supplied heat is instantly redistributed inside the metal shaping surface and transferred to the environment due to convective heat removal. Within the composite shaping surface of the tool, heat is not distributed so quickly because of the complexity of the composite structure and its specific insulating properties; therefore, heat supply to the moulded package is faster than convective heat removal from the other surface of the moulding tool.

The material and number of stiffening ribs of the moulding tool (n_y) are important as well, as illustrated in **Figure 7** where the highest value of heat removal is provided by steel ribs, which have maximum rigidity compared to the ribs made of aluminium alloy and fiberglass with the same dimensions of the ribs.

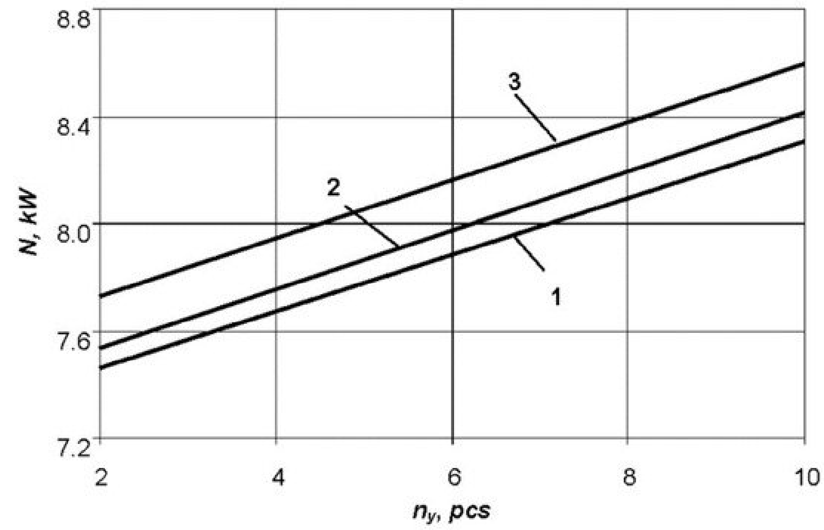

Figure 7. Graph of dependence of the power consumption on the number of stiffening ribs of various materials of the shaping surface of the tool: 1—fiberglass; 2—aluminium alloy; 3—steel.

Besides, the number of ribs changes the conditions for heat exchange with the surface. So, for a small number of aluminium ribs it is not possible to maintain the specified temperature–time regime for a fiberglass moulded package of 5 mm thick with the use of this equipment (**Figure 8**). However, when the number of stiffeners is increased to 10, the exothermic effect of the reaction is smoothed and the heating equipment can then cope with the task.

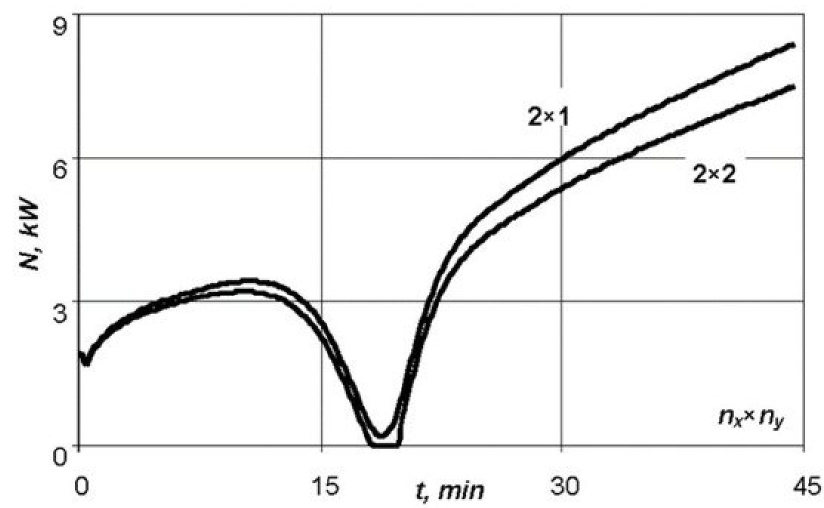

Figure 8. Graph of dependence of the power consumption on time for various numbers of aluminium stiffening ribs.

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