

Simulation of the curing of composite materials using microwave radiation with control of individual magnetrons

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Abstract. The traditional approach to the organization of the technological process of curing a binder polymer using microwave radiation is to rotate a workpiece around one axis in order to reduce the non-uniformity of its heating. Nevertheless, using this technical solution might lead to considerable difficulties when rotating larger workpieces, creating desired pressure on their surfaces and diagnosing the process. The approach suggesting that the workpiece itself remains stationary while the uniformity of its heating is achieved by creating a traveling electromagnetic wave in the operating area is to be considered a more promising direction in the development of curing technology. However, creating such a wave would require constructing a new and rather complex scheme for individual control of magnetrons, the theory of which has not been developed yet. The present work offers such a scheme of individual control and shows that using it allows to reduce the non-uniformity of the temperature field in a workpiece made of a polymer composite material with the maximum deviation of no more than 60 K, whereas the level of non-uniformity in the central part of the workpiece is not higher than 21 K. **Key words:** polymer composite materials, curing process, exothermic effect, microwave radiation, PID controller, individual control of magnetron.

1 Introduction

Currently, there is no generally accepted technology for the microwave curing of polymer matrix composites (PMC). At the same time, the majority of methods for heat treatment of the PMC by microwave radiation are based on the results of experimental studies. Thus, it was shown in [1] that using microwave radiation significantly reduces the curing time without deteriorating the characteristics of the resulting composite material. Other studies [2-5] have proved that using microwave radiation reduces energy costs of manufacturing PMC due to a significant reduction of the curing process duration by several times. Apart from that, the technology raises the quality of PMC by increasing the temperature uniformity in the workpiece. However, it is shown in [6-8] that using the radiation may also lead to an inhomogeneous distribution of the electromagnetic field in the volume of the operating area of the unit, and, as a result, to higher temperature differences, residual stresses and deformations. The issue resides in the fact that the intensity of the electromagnetic field in

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the operating area varies from higher to lower values. This leads to the formation of standing electromagnetic waves and in consequence, to creating wide temperature differentials. Traditionally, in order to equalize the temperature throughout a workpiece, it is rotated about one of the axes (about the central axis in case the detail is cylindrical). However, this approach poses new challenges, such as rotating a larger workpiece together with the mount, fixing the vacuum bag and supplying flexible vacuum hoses [9-13]. One possible solution to this issue may lie in readjusting the unit, so that the workpiece will remain stationary, and the uniformity of heating will be achieved due to creating traveling waves in the operating area of the unit. A large amount of experimental work in this field was carried out in [14]. However, the study neither provides a detailed mathematical or a physical model of the curing process, nor does it consider organization of the control scheme for operating the unit. The development and implementation of the suggested approach requires constructing a new and rather complex scheme of individual control of magnetrons, which appears to be currently non-existent.

2 Object of study

The current study of the dynamic of the curing process was carried out using a cylindrical PMC workpiece (fiberplastic reinforced using glass fiber with a volume fraction of 0.5, and a matrix made of epoxy resin). It was assumed that the cylinder with a length of 300 mm with an outer diameter of 100 mm and an inner one of 92 mm is positioned symmetrically in the operating area of a microwave curing unit. The operating area of the unit has the shape of a hexagonal prism with a height of 350 mm and a base circumradius of 106 mm. The magnetrons are placed on six outer lateral faces of the workplace at different heights relative to the bottom. The magnetrons positioned at an equal height are combined into levels. Notably, the number of levels with 6 magnetrons positioned on each of them (1 per face) may vary. Figure 1 illustrates one of alternative units equipped with 3 levels of magnetrons. In this work magnetrons with a power of 3,2 kW and a frequency of 2.45GHz were used as heating sources. The camera is assumed that the camera is made of metal and almost completely reflects the incident electromagnetic waves. For the simulation of electromagnetic wave propagation the workpiece material was assumed homogeneous and its complex permittivity was determined by Rayleigh's method [15, 16]. Other characteristics were calculated using Digimat modeling software. As a result, the following effective properties of fiberglass were evaluated: thermal conductivity, equaling 0.41 W/(m·K), density, measuring 2100 kg/m³, heat capacity of 950 J/(kg·K) and complex permittivity of 4.75 (1-0.023j).

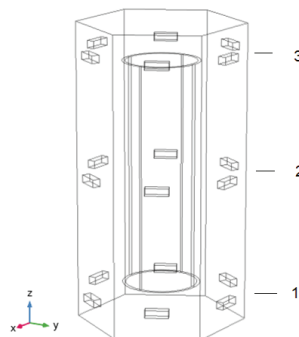


Fig. 1. The geometric model of the operating area, which is equipped with 18 magnetrons. The number in the figure corresponds to the level number.

3 The mathematical model of the curing

During the microwave curing simulation the following physical processes were considered: propagation of electromagnetic radiation in the volume of the operating area, absorption of the radiation in the workpiece with volumetric heat generation, liquid-solid transition of the matrix in the workpiece, volumetric heat generation in the workpiece due to the proceeding of exothermic process of matrix curing, conductive and radiation heat exchange in the workpiece between non-uniformly heated workpiece surfaces and the walls of the operating area [12, 17]. The physical model of the propagation of an electromagnetic wave was based on the next assumptions: metal walls of the chamber have high values of electrical conductivity and fully reflect the electromagnetic wave; the magnetron is a rectangular port (10mm x 20mm) that propagates an electromagnetic wave perpendicular to the surface; there is no reflection of the electromagnetic wave at the boundary surface between the internal volume of the operating area (air) and the PMC. The physical model of the heat transfer of the workpiece has the following presuppositions: the material of the workpiece is considered homogeneous and isotropic; on the lateral surfaces there is convective and radiative heat transfer with the environment; the shape of the workpiece does not change in the process; the curing process is exothermic and can be described by the one-stage Arrhenius equation; the ambient temperature is constant; the thermal and electrical properties of the material do not depend on temperature and do not change during the curing process. Currently, state-of-the-art approach for the heat treatment systems is to use the temperature control of the workpiece with the feedback loop [18].

In this work, it is proposed to apply a proportional-integral-derivative (PID) controller, which enhances the quality of the control process, reduces curing time and leads to a decrease of energy consumption.

For the implementation of PID it is necessary to determine the coefficients depending on the characteristics of the process [19]:

$$\tau_d = \frac{1}{2\zeta\omega}; \quad (1)$$

$$k = \frac{\omega}{2\zeta g}; \quad (2)$$

$$K_p = k(\tau_1 + \tau_2 - \tau_d); \quad (3)$$

$$K_i = k; \quad (4)$$

$$K_d = k(\tau_1 - \tau_d)(\tau_2 - \tau_d), \quad (5)$$

where ζ – damping ratio, ω – closed-loop frequency, rad/s; K_p , K_i , K_d – the coefficients for the proportional, integral and derivative terms respectively, τ_1 – first model time constant, s; τ_2 – second model time constant, s; g – model gain, K.

To calculate gain coefficients, curing process was simulated with the simultaneous operation of magnetrons at all levels with 30% of the nominal power. PID coefficients for this control scheme were found using calculated temperature at the characteristic points of the workpiece – $g = 83$ K, $\tau_1 = 9$ s, $\tau_2 = 382$ s, $K_p = 3,17$ 1/K, $K_i = 0.012$ 1/(s K), $K_d = 175.29$ s/K.

4 Modeling results

In order to achieve high values of the electric field intensity in the central area and on the edges of the workpiece, the rational dimensions of the operating area and the height of the individual levels of magnetrons were determined. The simulation of the electric field intensity in the operating area during the work of individual levels of magnetrons showed that enabling the magnetron located in the central part of the chamber (2nd level) creates maximum value of the electric field intensity (EFI) in that part, next to itself (fig. 2(a)). In contrast to that, the magnetron which takes place on the 3rd level produces high EFI on a large area (fig. 2 (b)), that allows to heat the most part of the workpiece. It is apparent that due to the symmetry of the arrangement of magnetrons relatively to the middle plane of the workpiece, the EFI values for the bottom and the top magnetrons are equal.

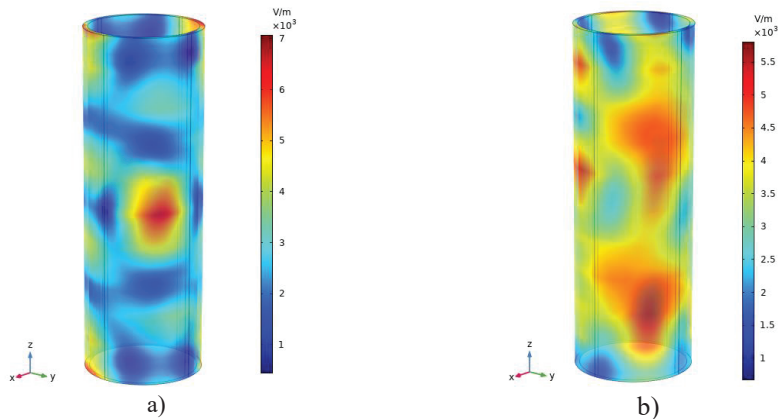


Fig. 2. Distribution of the electric field intensity in the workpiece, V/m, during operation of magnetrons: level 2 (a), level 3 (b).

Based on these distributions, the following scheme of magnetrons control was proposed (fig. 3), which provides the required temperature regime of curing. The first level was chosen as the baseline for the organization of magnetrons control. Having said that, the work of the next level is carried out with a time lag of 20 seconds relative to the base one. As a result, the third level has a delay of 40 seconds. Thus, the magnetrons work alternately. It means that only one magnetron at each level is enabled at each moment of time in order to make a traveling electromagnetic wave in the operating area.

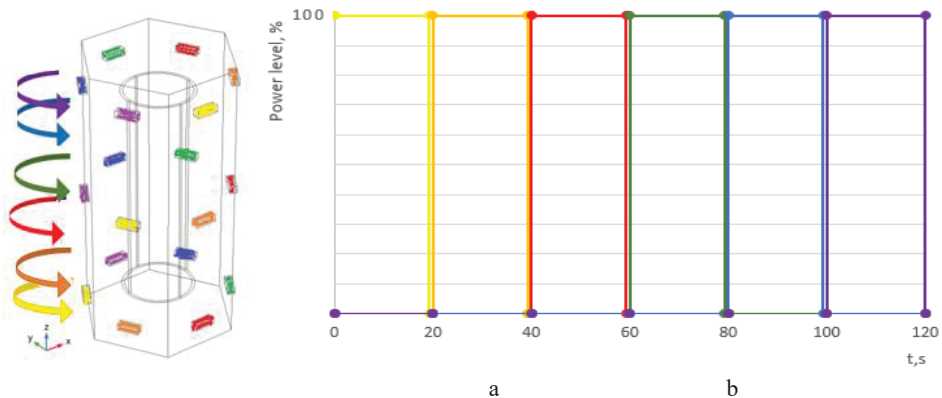


Fig. 3. Scheme of the magnetrons enabling order (a) and a schedule the magnetrons enabling (b). The magnetrons that have the same color are enabled sequentially, in the direction of the circular arrow.

The maximum temperature at a random point of the workpiece, which depends on time was used as an objective function of control of magnetron power (fig. 4).

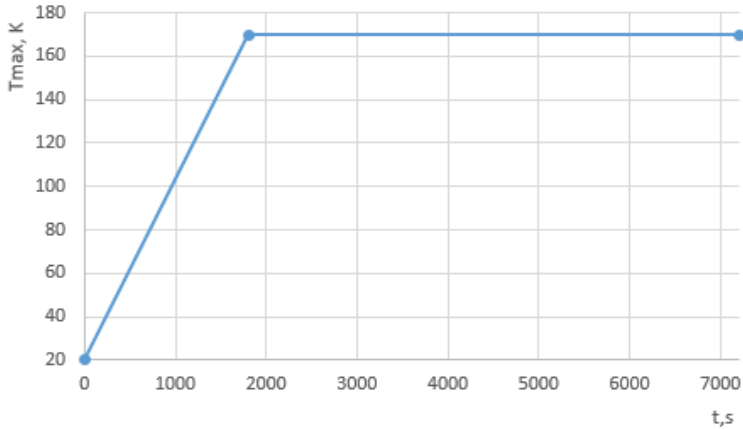


Fig. 4. Change in the maximum temperature of the workpiece.

To research the dynamics of the heating process and the degree of cure of the workpiece, the 7 test points were selected, that are located on the inner lateral of a cylinder in the top part of the workpiece (fig. 5). The analysis of the simulation results showed that there was a fairly uniform heating of the workpiece during the curing process except for its edge zones (fig. 6). It can be explained by the more intense heat removal from them. However, the degree of cure of the workpiece reaches the level of 98% during 3000 seconds (fig. 7-8 (a)). This result conforms to industry accepted quality criteria. It follows from the results that the deviation of temperature is less than 60 degrees (fig.8 (b)). The change of the magnetrons power that was obtained using PID controller is shown in figure 9. It can be seen that at the stage of maintaining constant temperature level in the workpiece (after 1800 s) power consumption of magnetrons is equal to 9600 W, taking into account the fact that three magnetrons are enabled at each moment of time.

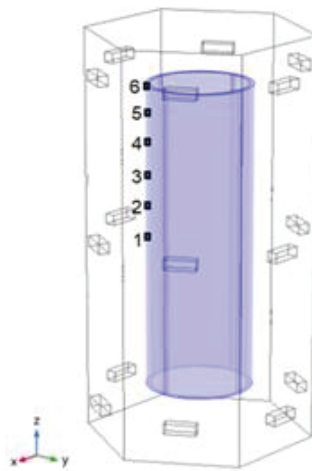


Fig. 5. Location of the test points in the operating area (the number corresponds to the test point number).

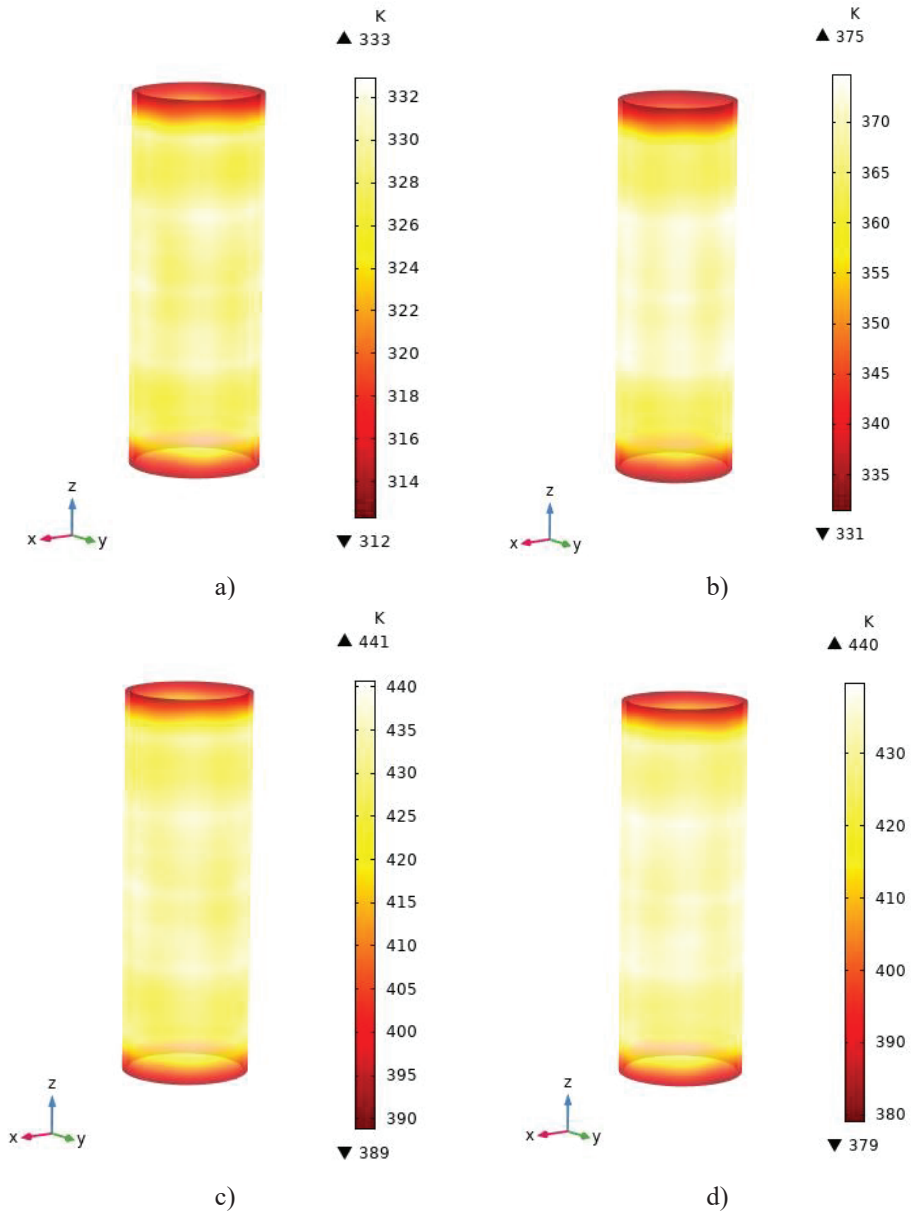


Fig. 6. Temperature of the workpiece at the time of 500 s (a), 1000 s (b), 2000 s (c), 6000 s (d), K.

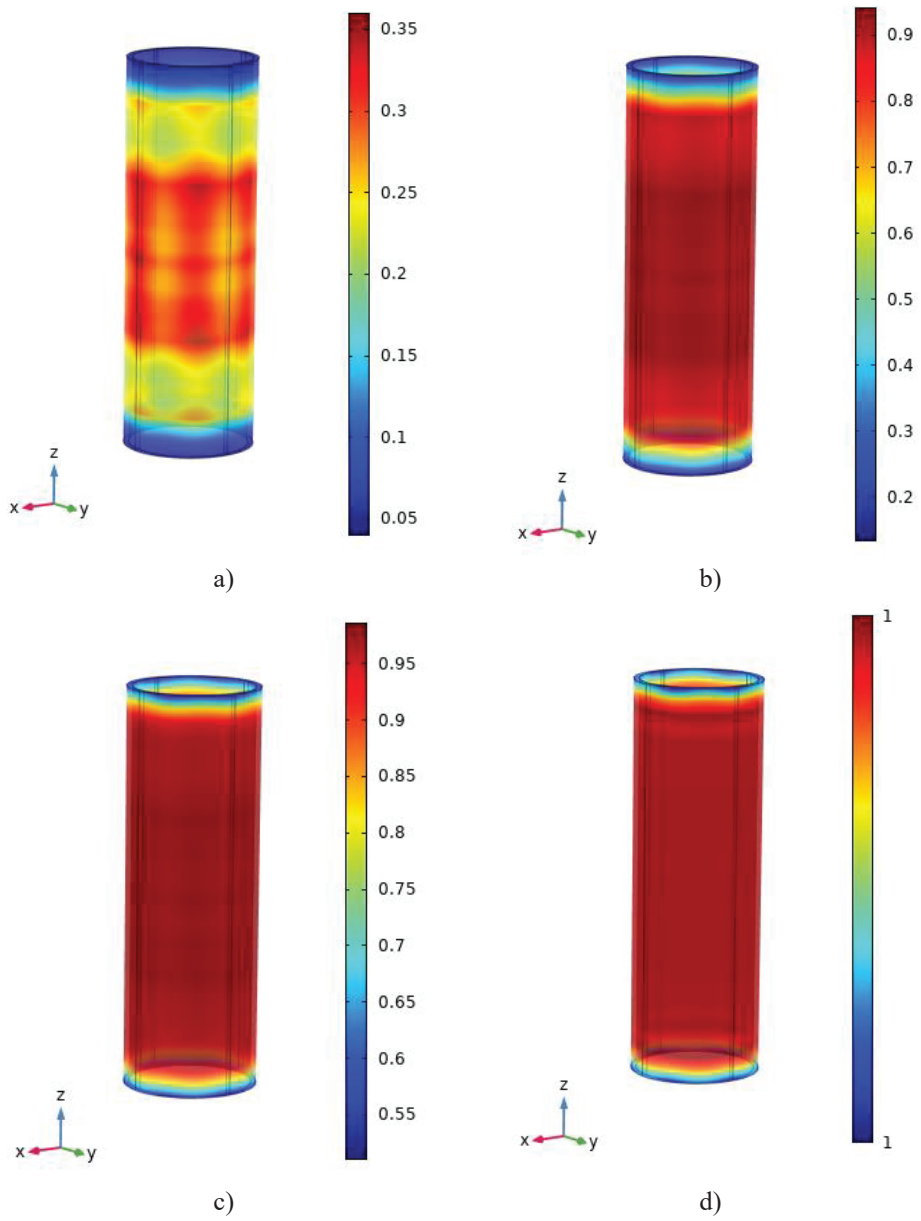


Fig. 7. Degree of cure in the workpiece at the time of 1000 s (a), 1500 s (b), 1700 s (c), 6000 s (d).

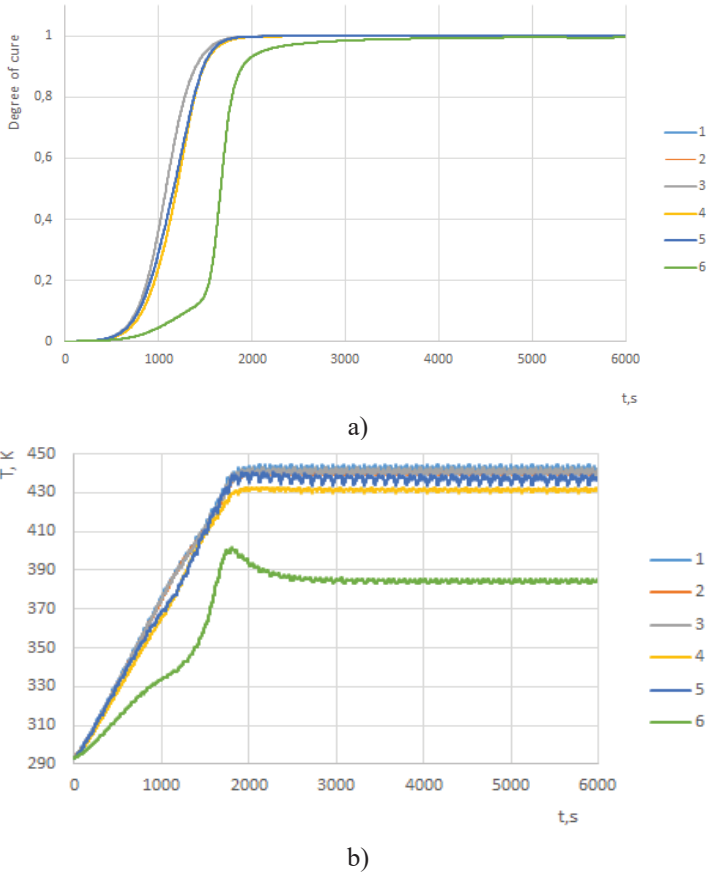


Fig. 8. Change in the degree of cure (a) and temperature (b) at the test points of the workpiece (the curve number corresponds to the test point number).

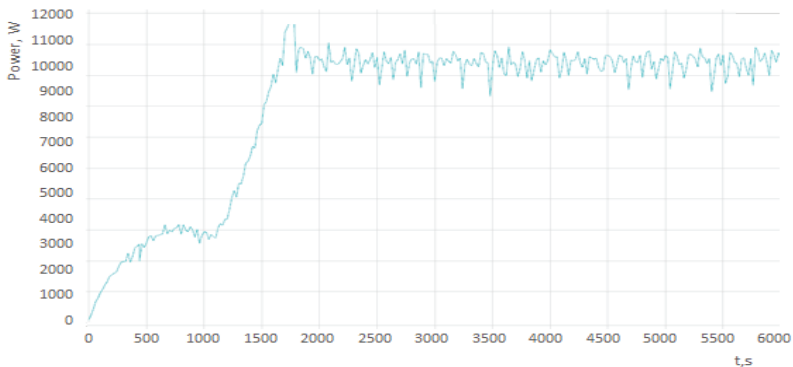


Fig. 9. Change in the total power of magnetrons.

5 Conclusion

A physical and a mathematical models of curing a polymer composite matrix under microwave radiation have been developed. The models describe such processes as propagation of electromagnetic radiation in the operating area, its absorption by the

workpiece with volumetric heat generation, heating of the workpiece and its heat exchange with the elements of the unit, exothermic effects arising from the curing of the binder. A scheme of the organization of the curing of a stationary workpiece has been proposed, providing independent sequential activation of magnetrons and individual control of their power. A mathematical model of a PID temperature controller has been created and its coefficients have been determined. It is shown that the using organized magnetrons allows to reduce temperature deviation to a level of 60 K and to complete curing of a workpiece in no more than 1 hour.

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