Application of induction heating in the FDM/FFF 3D manufacturing

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Abstract. This article addresses the problem of induction heating in its application to the FDM/FFF 3D manufacturing. One of the major problems of the FDM/FFF is the instability of layer-to-layer adhesion quality, and on the larger scale maintaining the homogeneity of material inside the whole printed object. Approach for mitigating and/or resolving of those problems, based on the fast and reliable control of the extruded material temperature during the printing process was proposed. Such approach uses specially created testbed system, consists of the ultra-low weight induction heated nozzle and fast temperature controller. This equipment enables rapid heating and cooling of the nozzle at low input power. On the contrary, using of the nozzle with the minimal thermal mass poses the problems of maintaining even heat distribution on the nozzle surface, and therefore inside the heated material. Multiphysics FEM model for the electromagnetic and thermal problem for the proposed nozzle and inductor configuration was formulated, and numerically solved using COMSOL 5.2a. Parametric optimization of the inductor form and heating signal frequency was conducted. Series of the experiments with the optimized inductor construction were made using the proposed testbed, showing significant increase of the heating speed and uniform heat distribution on the nozzle surface, and therefore in the final printed object quality. Experimental data for the all stages of conducted research is provided.

1. Introduction
At the beginning of the 21st century methods of additive manufacturing or 3D-printing [1, 2] due to their weak development were mainly used to create various prototypes. However, it is fair to say that by now a number of additive manufacturing technologies have reached the stage, when their application in the industrial production of functional products has become possible.

The most widespread 3D printing technology is fused deposition modeling (FDM), created in 1986 by S. Scott Crump [3, 4].

The essence of the technology is on building an object based on a digital model by depositing molten polymer material layer by layer on the platform through a heated extruder nozzle.

Most of existed FDM printers employ indirect resistive heating of the nozzle [5, 6]. The main disadvantages found in FDM/FFF 3D printing are related to its extruder and nozzle. These parts are
characterized by a big thermal mass of the heated part, low heating temperature, weak temperature gradient, low throughput capacity. High thermal inertia (lag) of the described system does not allow temperature adjustment during printing. This results in the instability of layer-to-layer adhesion, and on the larger scale – in material heterogeneity inside the whole printed object.

This study proposed to use the induction heating of the nozzle. A number of studies have presented systems for induction heating of the nozzle for 3D FDM / FFF manufacturing [7-15], however, they have significant thermal inertia and do not differ qualitatively from conventional systems.

Induction heating is a heating method, in which eddy currents are induced in an electrically conductive object placed in an alternating magnetic field, during the passage of which heat is generated in the volume of the object.

Physically/mathematically, the induction heating method is based on two physical laws: Faraday's law of electromagnetic induction and Joule-Lenz's law [16].

When a ferromagnetic material is heated by this method, the heat generation also occurs due to hysteresis losses [17]. For some materials heated, hysteresis losses may provide up to half of the heat generated. However this effect rapidly abrupts as temperatures approach the Curie point, after which the material becomes completely non-magnetic [18, 19].

Compared to the conventional indirect resistive heating induction heating has a number of major advantages.

This is the method of direct, non-contact electric heating and, in the general case, allows heating the exact area of a heated part surface to a higher temperatures within a short period of time and more efficiently than indirect resistive heating [20, 21].

These features enable to isolate the thermal mass of the heater from the thermal mass of the heated element. Therefore, an inductor acts as a heating element, and only a nozzle of the ultra-low thermal mass remains as a heated element. What is more significant, due to the ultra-low thermal mass of the nozzle, it provides rapid cooling.

While optimizing thermal mass, it is also important to take skin effect into account. The skin effect is a physical phenomenon consisting in the heterogeneous distribution of the AC density over the cross-section of the conductor: it reaches its greatest value at its surface and decreases with depth. At very high frequencies, the current practically exists only in a thin surface layer.

With increasing distance from the surface of the object, the current density decreases exponentially [22]. Moreover, the higher the frequency of the primary source of electromagnetic fields, i.e. inductor, the thinner the skin layer will be, in which about 85% of the heat is released. Heating of the internal volume of the object is mainly caused by its own thermal conductivity. Penetration depth also depends on electrical resistivity and relative magnetic permeability of heated object which varies with temperature [7, 23-28].

Thus, an approach to mitigate and/or resolve the problems of FDM / FFF technology based on the fast and reliable control of the extruded material temperature during the printing process is proposed.

When measuring the temperature by the eddy current method, the temperature is measured in the layers of material participating in the passage of currents of the selected frequency. By changing the parameters of the corresponding measuring signals, it is possible to obtain information about the temperature of various layers of the material (in depth). The operations principles of the fast temperature controller will be described in detail in another article.

The first aim of this study is to determinate heating signal frequency that meets the requirements for rapid nozzle heating. The second aim is to determinate inductor form that ensures uniform heat distribution on the nozzle surface to avoid local over- or underheating of the extruded material and localize the temperature measurement area. The physical constraints of the extruder design must be taken into account. It is also necessary to create a testbed system, consists of the ultra-low weight induction heated nozzle and fast temperature controller and enables rapid heating and cooling of the nozzle at low input power.
2. Multiphysics FEM model of induction heating process

2.1. Modelling problem settings and general description of physical processes

Multiphysics axisymmetric FEM model for the electromagnetic and thermal problem for the proposed nozzle and inductor configuration was formulated, and numerically solved using COMSOL 5.2a [29, 30].

An induction system for heating the nozzle in the FDM 3D printer contains the following: 1) a high frequency semiconductor source assembled according to the full bridge diagram (Fig. 1) with controlled phase shift [20, 21], 24V power voltage, power capacity up to 700W, frequency from 10 to 180 kHz; 2) inductor (Fig.2a) of a specified diameter and height, consisting of 20 coils of copper high-frequency wires; 3) a magnetic flux concentrator (Fig.2b) made of Supermalloy 79HM in the form of external cylindrical shell of the inductor; 4) an aluminium cylindrical mandrel (Fig.2c) that functions as shield against the high frequency magnetic field and as mechanical fastening of the heater to the extruder frame; 5) a nozzle (Fig. 2d) for FDM 3D printing of a preset configuration made of ferromagnetic alloy 40 x 13 with a tungsten carbide tip, which have inside channel of 2 mm diameter and 0.4 mm opening.

It is worth noting that the physical design of the inductor, concentrator, and other elements in the system is close to axially symmetrical one, which gives the opportunity to consider the induction heating system as a two-dimensional model, to use cylindrical coordinate system (0rz), and, therefore, to significantly simplify the process of modelling. Below we consider mathematical models of fundamental physical processes occurring in the system described when the nozzle is heated [31].

![Figure 1. Simplified circuit diagram of the induction heating power source.](image1)

![Figure 2. Drawing of the induction heating system for FDM 3D nozzle.](image2)

2.2. Electromagnetic task

To simplify the modeling, we assume that the load of the power source (inductor) is consistent, the oscillation frequency is adjusted automatically, and accordingly, at any specific time, the harmonic current $I$ of the known value flows in the inductor coil. In this case, the electromagnetic processes existing in such a system are described by the following system of differential equations in relation to a single-component complex magnetic vector potential $\hat{A}$: $\hat{A} = (0, \hat{A}_y, 0)$.

For the space area occupied by the working body:

$$j\omega \sigma \hat{A} + \nabla \times (\mu_0^{-1} \nabla \times \hat{A}) = 0$$

(1)

For the space area containing the $i$th inductor coil:

$$j\omega \sigma \hat{A} + \nabla \times (\mu_0^{-1} \nabla \times \hat{A}) = \frac{\sigma \hat{U}_i}{2\pi},$$

$$I = \int_{S_i} j\omega \sigma \hat{A}_y dS_i$$
\[ \dot{U}_i = \frac{S_i}{\sigma \int_{S_i} \frac{1}{2\pi r} dS}, \quad (2) \]

\[ \dot{j}_\varphi = -j\omega \sigma \dot{A}_\varphi + \frac{\sigma U_k}{2\pi}, \]

For the space area occupied by the magnetic flux concentrator:

\[ j\omega \sigma \dot{A} + \nabla \times (\mu_0^{-1} \nabla \times \dot{A}) = \frac{\sigma U_k}{2\pi}, \]

\[ \dot{U}_k = \frac{S_k}{\sigma \int_{S_k} \frac{1}{2\pi r} dS}, \quad (3) \]

\[ I = \int_{S_i} \dot{j}_\varphi dS = 0, \]

\[ \dot{j}_\varphi = -j\omega \sigma \dot{A}_\varphi + \frac{\sigma U_k}{2\pi}. \]

For ambient air:

\[ \nabla \times (\mu_0^{-1} \nabla \times \dot{A}) = 0 \quad (4) \]

In all the equations above: \( \sigma \)—the electric conductivity of the material (alloy 40 x 13, copper, tungsten carbide, Supermalloy 79HM, air); \( \omega \)—angular frequency; \( j \)—unit imaginary number; \( \mu_0 \) and \( \varepsilon_0 \)—magnetic and electrical permittivity of vacuum correspondingly; \( \mu_0 = 1.256 \times 10^{-6}, \varepsilon_0 = 8.85 \times 10^{-12} \) F/m; \( J_\varphi \)—current density in the inductor; \( r \)—radial coordinate; \( S_i \)—cross sectional area of the inductor; \( S_k \)—cross sectional area of the concentrator; \( U_i \)—originally unknown voltage drop at the ith inductor coil; \( U_k \)—induced voltage drop in the concentrator; \( I \)—electric current flowing in inductor coils (set value).

Full voltage value \( (U_\text{н}) \) across the inductor is defined as the algebraic sum of voltages defined in all the coils. The value of this voltage is used in calculation of active and reactive power consumed by the system. Frequency-related equivalent complex impedance in such a system is defined as follows

\[ Z = \frac{U_\text{н}}{I}. \]

Boundary conditions of the task described by (1)-(4) system can be considered a condition of symmetry about the z-axis and magnetic insulation at the external boundaries of the computational domain \( \dot{A}_\varphi = 0 \).

2.3. Thermal task

The inductor and the concentrator in the system under consideration are cooled due to thermal contact with the external cylindrical mandrel, which operates as a housing-radiator, and is mechanically connected to the extruder radiator that have a water cooling. To simplify the task, we assume that the thermal contacts are ideal and the extruder cooling is enough to provide for the cooling of the inductor and the concentrator. Accordingly, the temperature throughout them is constant and does not exceed the value of \( T = 50^\circ C \). Subject to this admission, the mathematical model of non-stationary thermal process of a workpiece induction heating can be described by only 2 equations:
\[ pC_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = \begin{cases} Q & \text{in the area of the heated nozzle} \\ 0 & \text{in other areas of the model} \end{cases} \] 

(5)

Here \( p = p(T) \), \( C_p = C_p(T) \), \( \lambda = \lambda(T) \) is the density, specific heat capacity and thermal conductivity of the material in the corresponding environment depending on temperature \( T \) (respectively); \( Q \) — specific capacity of the heat source that provides for the induction heating of the working area with whirling currents,

\[ Q = \frac{jj^*}{\sigma} = \omega^2 \sigma (\mathbf{A}_\varphi^* \mathbf{A}_\varphi^*) \]

(6)

\[ J = -j \omega \sigma \mathbf{A}_\varphi \]

where \( J \) is the working value of the induced current density within the ferromagnetic nozzle; \( \mathbf{A}_\varphi \) is a complex conjugate of the magnetic potential. Heat transfer in the form of convection and radiation in the system can be neglected due to the small contribution made by these mechanisms compared to the heat transfer in the result of the thermal conductivity of materials.

For this task, the boundary conditions can be accepted as the Neumann condition \( \frac{dT}{dr} = 0 \) on the axis of symmetry. In the area of the inductor and the concentrator having the forced cooling, we take \( T = \text{const} = 50 \) °C. At the external boundaries of the computational domain, we set the condition of heat exchange with the environment \( \frac{\lambda \partial T}{\partial n} = k(T - T_0) \), where \( k \) is the coefficient of heat transfer; \( T_0 \) is the environment temperature, \( n \) is an outward normal vector to the boundary.

To view these tasks in the ComsolMultiphysics interface we can use standard physical interfaces: Magnetic Fields (mf) and Heat Transfer in Solids (ht). The input data for the modelling are shown in the table 1 below.

| Table 1. Input data of a multiphysics model. |
|-------------------------------------------|
| Inductor                                   |
| material                             copper: |
|  electrical conductivity—5.998*10^7 S/m    |
|  relative magnetic permittivity—1        |
|  relative electrical permittivity—1      |
| number of coils                          20 |
| inner diameter, mm                      10 |
| outer diameter, mm                      15 |
| height, mm                              16 |
| power source voltage, V                 24 |
| oscillation frequency, kHz              5...180 |
| current, A                              15 |
| Magnetic flux concentrator               |
| material                             Supermalloy 79HM |
|  electrical conductivity – 0.01 S/m      |
|  relative magnetic permittivity—20000    |
|  relative electrical permittivity—4.5    |
| inner diameter, mm                      15 |
| outer diameter, mm                      16 |
| height, mm                              16 |
| Cylindrical mandrel, extruder housing-radiator |
| material                           aluminium: |
|  electrical conductivity – 3.774*10^7 S/m |
|  relative magnetic permittivity—1       |
relative electrical permittivity — 1
inner diameter, mm 17
outer diameter, mm 27
height, mm 12

Nozzle of the extruder

material steel 40 x 13
electrical conductivity — 1.12*10^7 S/m
relative magnetic permittivity — 5000
relative electrical permittivity — 1

height of the active part, mm 12
inner diameter, mm 2
outer diameter of the active part, mm 4
outer diameter of a thermal barrier, mm 3
height of a thermal barrier, mm 2
outer diameter of a nozzle shank, mm 6
height of a nozzle shank, mm 10

Nozzle of the extruder, tip

material Tungsten carbide:
electrical conductivity — 5.2·10^6 S/m
relative magnetic permittivity — 12
relative electrical permittivity — 1

height of the tip, mm 5
outer diameter of the tip, mm 5
inner diameter, mm 2
output opening diameter, mm 0.4

Additional data for thermal task solution

input environment temperature, °C 20
coefficient of heat transfer (environment), W/(m²/K) 15

coefficient of heat transfer (radiator with water cooling), W/(m²/K) 700
melt velocity in output opening, mm/s 100

Initial conditions make the following equations \( \dot{\psi} \big|_{r=0} = 0, T \big|_{r=0} = T_0, \psi \big|_{r=0} = 0, \rho \big|_{r=0} = 0 \).

Numerical implementation is carried out using finite-elements method in ComsolMultiphysics 5.2a applied software package. According to the multiphysics task classification, the connection between the listed tasks is weak, and they can be solved sequentially. In this case, the electromagnetic task is to be solved first; the solution shall be further used to solve the thermal task [32, 33].

3. Numerical realization

The results of numerical modelling of physical processes at \( f = 20 \) kHz and melt velocity in output opening \( v=100 \) mm/s, \( t = 4 \) s, are listed below. As it can be seen on the left side of the Figure 3, at the selected frequency, the penetration depth of the electromagnetic oscillation is significantly bigger in the endings of the nozzle working zone than in its middle part. This reduces the electrical resistance in relevant sections of the working zone, and, consequently, reduces the dissipated power (useful heating). The Figure 4 shows the temperature map of the extruder nozzle heating at \( t = 4 \), which reflects the described situation.
Figure 3. Results of the electromagnetic task at $f = 20$ kHz, $t = 4$ s.

Figure 4. Results of the thermal task at $f = 20$ kHz, $t = 4$ s, $v = 100$ mm/s.

More accurate temperature distribution in various sections of the heated nozzle can be seen in Fig. 5, which is a graph of temperature distribution for the vertical section (coordinate $z = -3...17$, $r = 1.05$ mm).

Figure 5. Temperature distribution in heated nozzle at $f = 20$ kHz, $t = 4$ s, section $r = 1.05$ mm.

The Figure 5 shows the nozzle temperature reached 78 °C at $t = 4$ s, that does not meet the requirement of rapid heating. Therefore, 20 kHz frequency is not efficient for heating the nozzle. Besides, the temperature difference in the central part of the heated nozzle is 28 degrees compared to the periphery (50 degrees for the point on $z = 17$, 78 degrees for the point on $z = 11$). Such unevenness leads to local overheating (not critical) of the extruding material. In addition, it should be noted that one of the main parameters affecting the quality of printing is a temperature gradient in the thermal barrier zone (Fig. 2, $z = 15 ... 17$ mm). The temperature difference in this area must be enough to rapidly reach the glass transition point. The most high-quality printing is achieved at an ultimately rapid temperature change (minimum height of the formed plug).

Since the main reason of the disadvantages listed above is uneven heating of the working zone of the nozzle caused by uneven penetration of electromagnetic oscillation during the induction heating, it was decided to optimize the heating frequency since this parameter directly affects both the depth of penetration and the overall distribution of electromagnetic oscillation in the inductor. The corresponding parametric task with such a variable parameter as heating frequency was numerically solved using ComsolMultiphysics modeling environment for the whole operating range of the source
frequency (10 .. 180 kHz) with a parameter step of 10 kHz. To save the space, the following consolidated graph shows the temperature distribution lines similar to those shown in Fig. 5.

As shown in the Figure 6, the slow growth in the heating efficiency is observed along with increase of the heating signal frequency. The frequencies ranging from 20 to 150 kHz are characterized by parabolic shape of temperature distribution curve in the working part of the nozzle (from \( z = 5 \) to \( z = 17 \) mm) with a growing slope of the corresponding parameter.

![Graph showing temperature distribution](image)

**Figure 6.** Solution of thermal part of the parametric multiphysics task at \( f = 10. \text{ to } 150 \text{ kHz} \). Temperature distribution in heated nozzle (\( z = -3 \ldots 17 \)) at \( t = 4 \text{ s} \), \( v = 100 \text{ mm/s} \), section \( r = 1.05 \text{ mm} \).

As a result the heating signal frequency was accepted as 120 kHz. This frequency provides high efficiency and heating rate. Figure 6 shows the nozzle temperature reached 400 °C at \( t = 4 \text{ s} \). At the same time, the temperature difference in the central part of the heated nozzle is 130 degrees compared to the periphery (270 °C for a point with \( z = 17 \), 400 °C for a point with \( z = 11 \)).

To eliminate such a significant uneven distribution of the temperature in the working part of the nozzle, an additional stage of modeling was completed with a change in the form of the inductor (Fig. 7). Selecting an even higher heating signal frequency would require deep optimization of the inductor form, while it is limited by the physical requirements of the extruder housing.

![Modified form of the inductor](image)

**Figure 7.** Modified form of the inductor.

Taking into account the observed heating curve shape, it was decided to modify a form of the coiling base and the thickness of the inductor in some parts (after such a modification the inductor will have the form of a truncated sphere, rather than of a hollow cylinder). In terms of models, it is reflected in truncation and extrusion of the corresponding parts of the inductor. An additional
parametric multiphysics task was created and resolved to parameter indform – point coordinate along axis r, that limit the variable part of the inductor. After modifying the form of the inductor for the obtained system configuration, the previous parametric task was solved once again at f = 10 ... 180 kHz (Fig. 8).

Figure 8. Solution of thermal part of the parametric multiphysics task at f = 10.. 150 kHz with modified inductor form. Temperature distribution in heated nozzle (z=-3...17) at t = 4 s, v=100 mm/s, section r = 1.05 mm.

On the basis of the data presented in Fig. 8 we can conclude that the modification of the inductor form significantly reduced unevenness of the temperature distribution in working part of the nozzle. The temperature spread in working part of the nozzle (z = 5 … 11 mm) was no more than 10 °C, which is a fairly good result. Figure 8 shows the nozzle temperature reached 300 °C at t =4 s, f = 120 kHz, which is an excellent result and meets the requirements of rapid heating. More accurate temperature distribution in various sections of the heated nozzle can be seen in Fig. 9, which is a graph of temperature distribution for the vertical section (coordinate z=-3...17, r = 1.05 mm).

Figure 9. Temperature distribution in heated nozzle with modified inductor form at f = 120 kHz, t = 4 s, v=100 mm/s, section r = 1.05 mm.
It is worth noting that the optimized option is characterized by a much more rapid temperature change in the thermal barrier part, which results in the reduction of the transition zone height from 10 mm to almost the height of the thermal barrier (2 mm), which is an extremely high result. For example, for PLA plastic, the glass transition temperature is only about 65 °C, and the melting point is about 170 °C [34]. At the same time, for ABS plastic, the glass transition temperature is 105 °C, and the melting point is about 210 °C. According to the data shown in Figure 9, the height of the plug-piston for both types of plastic is about 2 mm.

4. Experimental confirmation of the modelling results
To confirm the results of the completed numerical modeling the testbed system was created, which comprises laboratory power supplies with U = 24V, Imax = 30A, DRV8302-based power controller, back end with MOSFET transistors, and Control Board based on ARM-micro controller STM32F334R8 by STMicroelectronics. Rated values of elements in LLC-resonance circuit were converted to fit the operating frequency of f = 120 kHz. The modified inductor was formed with 20 coils of copper litz wire (d = 0.75 mm, 2 layers). The geometry of the induction extruder complies with the one shown in Fig. 7. The appearance of the pilot extruder as well as the ferromagnetic nozzle are shown in Fig. 10, 11.

The induction extruder was mounted on a 3D printer, whereupon a number of experiments were conducted to assess the performance of the extruder.

For the experiment, nylon was chosen as the test material, because this polymer is highly sensitive to the extrusion temperature (a temperature deviation of 5-10 degrees leads to a significant change in the characteristics of the printed product, a decrease in strength, changes in external parameters (product color, shape of the extruded line), as well as to uniformity of heating (uneven heating during extrusion leads to the formation of visible bubbles in the extruded material). Several samples were made (parallelepiped with a base of 30 x 30 mm and height of 5 mm). The printing output is shown in Fig. 12. All samples printed at an extrusion speed of 5 to 100 mm/s (for a nozzle of 0.4 mm) demonstrate identical appearance and mechanical characteristics, which indicates a high uniformity of heating of the material, as well as the achievement of an accuracy of keeping the temperature of the nozzle in the range of + -3 °C.

The results of the completed experiment showed a significant increase in printing quality (absence of spurious plastic efflux, absence of overheated areas with temperature-driven changes in filament color).

An increase in the heating rate of the nozzle has been achieved. From 20 °C to 300 °C, the heating time is 2-3 s. against 40-90 s. in standard three-dimensional printing systems.
Figure 12. Appearance of the test product surface printed of nylon.

Figure 13 shows a graph of heating and cooling of the nozzle, which characterizes the quality of the developed induction heating system. Within 10 minutes, several cycles of heating and cooling were performed. The nozzle was heated from 30 to 300 °C. During the first cycle, the nozzle was gradually cooled by 50 °C in a step up to 50 °C. During the second cycle, the nozzle was cooled to 50 °C in one step. The temporary cooling characteristics of the induction heating system and the hot part of the standard extruder are shown in table 2.

Table 2. The temporary cooling characteristics of the induction heating system and the hot part of the conventional extruder.

| Initial temperature/final temperature, °C | Induction heating system, cooling time, s | Hot part of the standard extruder, cooling time, s |
|------------------------------------------|------------------------------------------|-----------------------------------------------|
| 300/250                                  | 5                                        | -                                             |
| 250/230                                  | 3                                        | 22                                            |
| 250/200                                  | 9                                        | 60                                            |
| 200/150                                  | 13                                       | 80                                            |
| 150/100                                  | 22                                       | 120                                           |
| 100/50                                   | 82                                       | 250                                           |
| 250/50                                   | 120                                      | 450                                           |

The data shown in the table 2 and on the figure 13 demonstrate a high speed of both heating and cooling of the nozzle is provided.
5. Conclusion
The advantages of induction heating over the indirect resistive heating method are revealed. Namely: the possibility of rapid heating and cooling of the nozzle, the ability to ensure uniform heating of the nozzle and the extruded material, the ability to provide a high temperature gradient in the thermal barrier part between the hot and cold parts of the nozzle.

Multiphysics axisymmetric FEM model for the electromagnetic and thermal problem for the proposed nozzle and inductor configuration was formulated, and numerically solved using COMSOL 5.2a. As a result of the simulation, the heating signal frequency (120 kHz) and the form of the inductor were determined. The temperature spread in working part of the nozzle (z = 5 ... 11 mm) was no more than 10 °C. Transition zone height reduced from 10 mm to almost the height of the thermal barrier (2 mm).

The testbed system, consists of the ultra-low weight induction heated nozzle and fast temperature controller created to confirm the results of the simulation modeling showed a significant increase in print quality.

The opportunity of reliable control of the extruded material temperature during the printing process is provided. From 20 °C to 300 °C, the heating time is 2-3 s. against 40-90 s. in standard three-dimensional printing systems. A decrease in the cooling rate of the nozzle has been achieved. From 250 °C to 230 °C, the cooling time is 3 s. against 22 s. in conventional three-dimensional printing systems.

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