International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2022 | Issue 51 | Volume 14 | Number 2 | Pages 74-83

3D MATHEMATICAL THERMAL ANALYSES OF PA12 POWDER BED ON THE SLS PROCESS BY TWO NUMERICAL METHODS

H. Yaagoubi   H. Abouchadi   M. Taha Janan

Laboratory of Applied Mechanics and Technologies (LAMAT), ENSET, STIS Research Center, Mohammed V University, Rabat, Morocco, hanane.yaagoubi@um5s.net.ma, abouchadi@gmail.com, m.tahajanan@um5s.net.ma

Abstract- The SLS (selective laser sintering process is a manufacturing process for parts with complex geometries based on the laser projection of polyamide powders on a substrate. The process includes significant local temperature variations causing the appearance of residual stresses in the parts. In this work, we propose a three-dimensional numerical simulation model of the coupling of thermal phenomena induced by sintering of a Polyamide12 layer by layer using laser projection. This mathematical model depends on this model is based on the coupled solving heat transfer mathematical model; the laser source was being modeled as a surface heat source distribution. The model is implemented in different forms one and three-dimensions finite difference method using Matlab software. The results of the numerical simulation are compared with the methodology obtained experimentally of the work of authors Omkar Deshpande and Daniel Moser and analytical solution of author Franco and with our numerical simulation by meshfree method. In our propositions the calculations are performed within the point focus of the laser in the polyamide converting of polyamide numerical calculation shows the detection of heat in the point focus of the laser is under the temperature of fusion in the polyamide powder. Our investigations shows also that all the parameters influence maximal heat under the laser beam on the coat bed of the selective laser sintering process like power laser, radius spot laser, pre-hating temperature etc. The whole of these conclusions approve that life forecast of parts worked 3D printing, for example, selective laser sintering require an excellent physical characters.

Keywords: 3D Finite Difference Method, 3D Meshfree Method, Nonlinear Problem, Polyamide12, Selective Laser Sintering, Thermal Calculation.

1. INTRODUCTION

Three-dimensional printing is a family of technology allowing a part to be manufactured from a design of numerical file by adding layer, also it's possible to use a different materials like polymers, bio material, etc.

The selective laser sintering process (SLS) produces a three-dimensional polyamide part, which consists in melting the powder bed by a CO_2 laser beam [1-4]. which solidifies, the deposited material which forms a track. This process is used in several fields of industry, in particular, aeronautics, bio-medical, art, etc. [5-9]. because it allows building really complex shapes, and using the topological optimization methods, which can offer great weight saving opportunity, which can save production time and cost [10-13]. This process is joined specifically by state change (melting and solidification of matter) [14-21]. The large thermal gradients during the cycle are the reason for the presence of appearance of residual stresses in the parts. The goal of our investigation is to create a mathematical modulization in three dimensions of the of the heat transfer evolution at the first converting powder based on the modeling of thermal phenomena induced by the selective laser sintering process like convection and radiation phenomena. To our knowledge, in this process, several parameters of the machine and the material are always in relation (Table 1), like the diameter of the spot laser, the power of the laser, the preheating temperature, thermal conductivity, specific heat, density energy, porosity, the ambient temperature. [6-10]. This mathematical theoretical study was developed to understand the thermal history inside the selective laser sintering process.

1.1. The Powders and their Characteristic Temperatures for the Process

The printer preheats the powder to a distribution of the heat slightly under the fusion of the raw material of Polyamide12. This preheating allows the laser to more easily boost the heat of specific areas of the material covering traces the shape of the model to solidify the part [5]. Cooling is induced by the arrival of the new layer, which is cooler than the molten material [1]. It is necessary not to pass the molten material below its crystallization temperature in order to keep it in the liquid state as long as possible. This is why the powder in the polyamide powder bed is preheated.

However, this preheating is limited, on the one hand by the melting temperature of the material used so as to not generate a change of situation, on the other hand by the influence of the heat on the flowability of the powder [9]. In the case of Polyamide12 preheating of the order of 170-175 °C, under the fusion heat of the powder is recommended.

The polyamide powder bed is retain at temperature equal to 80 °C. Heating of the manufacturing zone following the spreading of a layer of powder at a temperature allowing good flowability (80 °C for PA12) [1], [6], then should be preheated at a fusion degree temperature (T_f = 184 °C for PA12) to confirm ideal setting for its upkeep in fluid state after heat flux, sensors radiant heaters are activated briefly previously of the scan laser in order to carry the layer to a temperature of around 10 °C underneath it's liquefying temperature [11-17]. Pre-heating phase in the case for example of other type of polyamide like a PEEK material is around 340 °C [7].

The pre-heating temperatures must be maintained very precisely: a variation of 4 °C induces a reduction in density of the material after melting of 4% for a Polyamide12 [11], The radiators are therefore controlled with PID correctors [8]. The 3D system company proposes, for a PA12, to raise the temperature to the starting point of melting of the material and then to decrease it by 12 °C.

1.2. Laser-Matter Interaction

The laser-to-matter interaction is dependent on the frequency of laser radiation, formula of material and its level of hotness temperature [8]. On massive metals, absorption occurs at very reduced depths (< 50 nm) by free electron-photon interaction, and can therefore be modeled as surface. exponential law which describes this interaction [11] in depth of the Beer-Lambert type, whether for UV or IR radiations, in various works allowing to determine a concordance between the model and the experimental studies [15] [18-19]. In the literature on this subject [22-32], a finite element model is presented by [3] of a domain representing powder sintered, In the work of [13-14] talk about phenomena of coalescence phenomena which is fast and the appearance of porosity in the printed parts on the laser sintering process. The [11] established that parts mechanical properties are dependent on the temperature at which it was sintered.

The SLS process was modeled in one and three dimensions by two numerical methods, the melting of the powder by heat flux laser, programed by Matlab software, after different simulations that a correct programming then, is required to Decide the effect of the parameters on the high level of the temperature in focus spot laser which T(°C) = 178. And the maximum temperature should not be exceeded the maximum temperature. Polyamide12 parts were chosen in this study because it remains the polymer is the most material used due to its ease of processing [24].

In addition, the professional laser sintering Polyamide12 material has a moderately huge temperature margin [37] and although there is an ideal handling temperature that taken from the most outstanding mechanical conditions. The LS materials are frequently chosen by their sintering window. The sintering window is generally characterized as the area between the melting endotherm peak and the exothermic crystallization peak in the DSC analysis in the DSC examination.

The bed temperature of LS systems is usually set within this range for semi-crystalline polymers because it allows effective part consolidation by avoiding premature crystallization on cooling [34]. In order to achieve effective sintering, a wide sintering window is desired with neither double melting peaks nor overlapping melting and re-crystallization peaks. The LS is the most encouraging method to create polymer parts of superior [33-41]. the polymers generally require high processing temperatures which are generally not reached with the usual LS processes. all the thermal phenomena react in the bed of Polyamide12 powder, are: conduction, convection and radiation. The considerable investigations have been founded on thermal model in the selective laser sintering in the literature [8-13], in this work, the studied of the non-linear due to the radiation terms.

2. THERMAL MODELING OF SLS PROCESS

To accomplish the objective of thermal modeling, the further improvement of the surface temperature of Polyamide12 powder bed is over time is important. Transient heat transfer conditions are made under these propositions [10], [17].

A global model shows the heat side of the powder bed, thinking of heat transfer at the surface and thinking of convection and radiation as heat losses.

- The polyamide covering is homogeneous
- Measurement of the polyamide covering temperature under the laser spot.
- The thermal property coefficients were considered constant (no change with temperature) [1], [13-14].
- The problem is nonlinear due to dependence as the thermal capacity of the material and accepting constant thickness and thermal conductivity.

2.1. Non-Linear Mathematical Model Solving by Difference Finite Method

In this section, a three dimension of finite difference method approaches are introduced to predict the temperature field in laser-based Polyamide12, SLS process and to calculate the high level of distribution heat in the point focus of the laser. The temperature field is predicted with steady-state heat source q.

The laser project is along the direction (z-axis) and deposited its energy to melt the Polyamide12 powder [3-10]. The heat loss due to convection and radiation is considered in this modelling, the three-dimensional problem is based on solving the following the three-dimensional heat transfer Equation (1) [1-11], [11-18]:

$$\frac{\partial T}{\partial t}=\frac{K_e}{C_p\rho}\left(\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}\right)+q \qquad (1)$$

The one-dimensional problem is also treated by the following one-dimension heat Equation (2) [17]:

$$\frac{\partial T}{\partial t}=\frac{K_e}{C_p\rho}\times\frac{\partial T^2}{\partial z^2}+q \qquad (2)$$

where, ρ is the density, C_p is the specific heat, K_e is the thermal conductivity of Polyamide12 is proposed constant by the author [5-6] and cited by [34], T is the temperature, t is the time, q is the heat source model at the surface.

The initial and boundary conditions are described as follows:

The powder bed is preheated under 150 °C [32], for $t = 0$ s, $T(x, y, z) = 150$ °C in Equation (3) (Pre-heating temperature).

The boundary conditions the convection fluxes and the radiation on the covering of the Polyamide12 powder are imposed along the z axis:

$$-K_e \frac{\partial T}{\partial z} = 0 \tag{3}$$

$$-K_e \frac{\partial T}{\partial z} = h\left(T_e - T_z\right) + \sigma\epsilon\left(T_e^4 - T_z^4\right) \tag{4}$$

The material picked for this examination is Polyamide12, where the actual properties were viewed as constants (Table 1). In different works, there are a few details laser source as source of energy which is described like as input energy during the SLS process, in this article, q [W/m²] is the heat flux laser calculated by [31].

$$q = \frac{P}{\pi r^2} \tag{5}$$

2.2. Finite Differences Method

The finite difference method is in mathematical investigation, the limited distinction strategy is a typical method for tracking down estimated arrangements of partial differential equations [43]. Note that in this part, the index notation is used whose principle is as follows: If u (X, t_k) is a function which depends on a time variable t_j and on one or more spatial variables (X_i) $n_i = 1$. It is writhed u $(X, t_j) = u_k - i_1, i_2, \ldots$, then it is denoted at any time $u(x_i, t_j)$ by u_i^j. It is seen that the second partial derivative of u has been approximated by the limited expansion formulas which concur with those of Taylor because the function is continuous, Equations (6)-(19).

Let us recall this approximation here [28]:

$$\frac{\partial^2 u}{\partial x^2}(x_i, t_j) = \frac{u_{i+1}^j - 2u_i^j + u_{i+1}^j}{(\Delta x)^2} \tag{6}$$

$$\frac{\partial u}{\partial t} = \frac{u_i^{j+1} - u_i^j}{(\Delta t)} \tag{7}$$

$$\frac{u_j^{i+1} - u_i^j}{\Delta t} \simeq \frac{k}{c\rho} \times \frac{u_{i+1}^j - 2u_i^j + u_{i-1}^j}{(\Delta x)^2} \tag{8}$$

$$r = \frac{\Delta t}{(\Delta x)^2} \times \frac{k}{c\rho} \tag{9}$$

Replacing these approximations in the heat equation, the following formula is found:

$$u_i^{j+1} = r u_{i+1}^j + (1 - 2r) u_i^j + r u_{i-1}^j \tag{10}$$

In the next section, the corresponding numerical results will be presented.

3. NUMERICAL THERMAL ANALYSIS

The layer of the Polyamide12 powder is simulated in the form of a rectangle of dimension 5×2×1 mm (Figure 1). The laser is considered perpendicular to the powder bed (Figure 2). The calculation of the temperature in the covering of the layer is in the center of the spot of the laser.

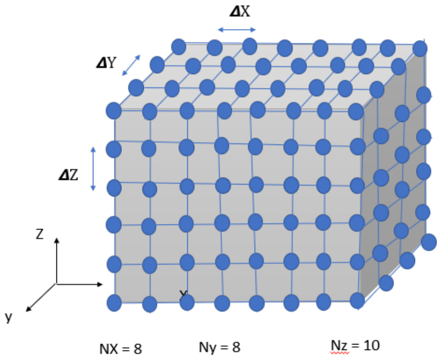

Figure 1. The meshing by the finite difference method

3.1. Parameters Calculations Methodology

Based on our knowledge, few studies have treated the nonlinear of thermal phenomena in the selective laser sintering process. Other interesting studies are those done by Omkar Deshpande [32] who found a methodology to calculate the maximal temperature converging of powder in the point focus of the laser CO_2 physical properties of laser power, scan rate, laser spot diameter and other machine parameters affect the change of melting and cooling state of powder [38-41].

In this paper a full theoretical analysis of the non-linear thermal analysis of selective laser sintering of Polyamidep12 was presented, in such a situation does not admit an exact solution, the exact solution proposed by author Franco has been founded [17] without taking into consideration convection and radiation phenomena, so only a numerical approach makes it possible to determine the most real and correct states of energy. In order to solve this problem, we use a finite difference method based on the resolution of the heat equation transfer.

For a better comprehension of all the thermal phenomena which react in the SLS machine, the result of our finite-difference code has been compared with the methodology calculations of Omkar [32] and experimental work of the author [14], and also between our finite difference code and our simulation by Meshless method under Matlab and also a comparison with the analytical solution of author Franco [17] has been done, after this introduction. The results are discussed in Section 3, and the final remarks are given in Section 4.

First of all, in this work, section, the result is adequate with methodology and experimental work of the author [32] which basic heat transfer equation is used for calculating the heat of point focus of the laser of powder bed in the SLS process under these assumptions:

- It is taken into consideration (C_p) equal to 1700 (J/kg-K)], (ρ) equal to 1130 (kg/m^3)] are assumed to be the same as that of the bulk material [32].
- The value of the temperature of sintering T_f is proposed to be inferior a 10 of the fusion temperature (185 °C) [32].
- Preheated powder temperature (T_i) is 150 °C. (section 5 in [32]).
- They are any Energy loses to take into consideration.
- Absorptivity (A) is 0.1, and spot laser diameter (D) = 700 µm.

- William and Deckard find that energy density increases the product point size of parts.
- This is due to the large exposure of the laser, normally the laser spot diameters of SLS machines do not exceed (0.5-0.7 mm) [32], h = 150 µm, v = 30 mm/sec [32].
- So, this is methodology of the calculation by the author [32]:

Pulse energy to sinter a spot size of diameter d and layer thickness, h from [32],

E_n = Mass flow rate × Sensible heat / Absorptivity

$$E_n = \rho\pi d^2 h \frac{T_f - T_0}{4A} \quad (11)$$

$$E_n = 0.028213124 \text{ J} \quad (12)$$

Power required for sintering a spot of spot size:

$$d = E_n / t \quad (13)$$

$$t = d / V \quad (14)$$

$$t = 0.7 / 30 \quad (15)$$

where, d is Diameter (mm) and V is scan speed (mm/sec).

$$t = 0.02333 \text{ sec} \quad (16)$$

Power required for sintering a spot:

$$p = 0.028213 / 0.0233 \quad (17)$$

$$P = 1.2091 \text{W} \quad (18)$$

All these parameters obtained from [32] will be used in our finite difference simulation under Matlab.

Calculation of time per interaction (tt):

$$tt = d / V \quad (19)$$

Figure 2 presents a general flow chart of the SLS thermal process based on the finite difference method; this general flow chart will focus on the main processing parameters directly associated with material properties. As processing parameters, laser power, and the diameter of the laser, Preheating temperature etc.

The rectangular part has been chosen with a dimension of 1×2×5 mm (Figure 3) and the calculation of high temperature will be done in the point focus laser inside the selective laser sintering process.

4. RESULT AND VALIDATION

4.1. First Validation

The maximal temperature has been calculated of high temperature point focus under laser inside the selective laser sintering process, using finite-difference code that is programmed to resolve the mathematical thermal model.

For the first validation, it's important to validate the thermal model and numerical simulation with the experimental methodology of the author [32] described in paragraph (A) (Parameters Calculations Methodology) whose conditions used in the author's experiment [32] are given in Table 1.

Figure 4 shows the numerical simulation of the laser projection of a layer of PA12 powders. The Figure 4a shows the temperature evolution at the upper surface (z = 0) and along z of the powder bed of Polyamide12 (Figure 4b). The temperature fields recorded at these points are close enough to be able to consider that it quickly reaches the steady-state.

It is also noted that That the high value temperatures is close to the value of liquidus temperature of the Temperatures, (178 °C) of the Polyamide12 which is correct as thermal modulization, high and restricted detected in the inside of SLS machine the passage of the laser source. The comparison of our result with the methodology study of the author [32], gives us the validation of our thermal model taking into consideration the radiation and convection boundary conditions which the progression of temperature is proposed to be 10% under the fusion point (185 °C) [32], at exposure time t = 0.023 s calculated by Equation (15). The maximal temperature under the laser spot was founded in our simulation is 172.2 °C and this is very close enough of the result of work [32].

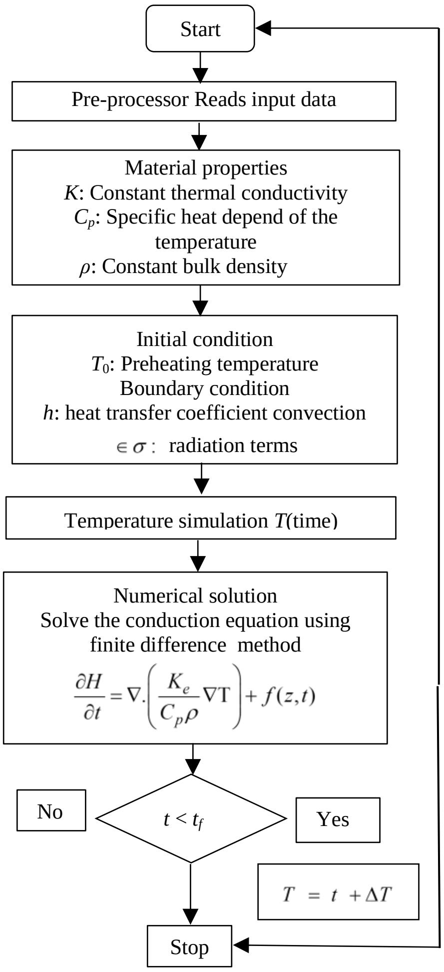

Figure 2. General organigram application of numerical method process based on the finite difference method

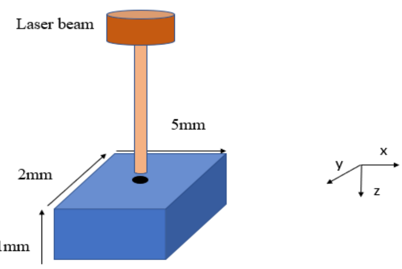

Figure 3. The situation of the point at the surface of the powder bed

Table 1. Parameters of laser source for the first validation

Thermo-physical properties	Full name	Value	Unit	Ref
K_e	Effective thermal conductivity	0.23	W/mK	[32] [30]
T_0	Initial bed temperature	150	°C	[32]
C_p	Specific heat	1700	J/kg/K	[32]
σ	Stefan-Boltzmann coefficient	5.67×10^{-8}	$W/m^2/K^4$	[32]
$\in$	porosity	0.8		[32]
ρ	Initial density	1130	Kg/m^3	[32]
h	Convection coefficient	25	J/cm^2K	[32]
T_e	Temperature of the chamber	150	°C	[32]
P	Mean laser power	1.2091	W	[32]
r	Laser beam Rayon	0.00035	m	[32]

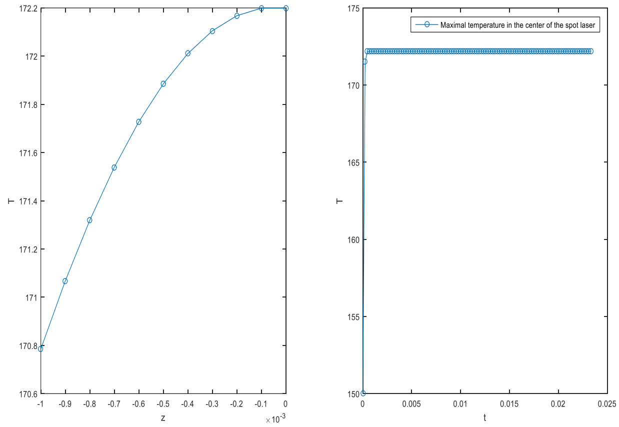

Figure 4. (a) Development of the temperature at the upper surface, (b) along z of the powder bed of PA12 inside SLS at exposure time t = 0.023 s by finite difference method

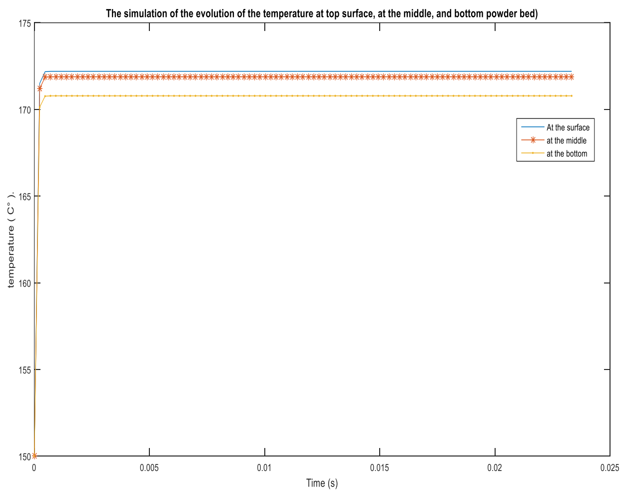

Figure 5. The simulation of the evolution of the temperature at top surface (z = 0), at the middle (z = 0.5 mm), and bottom powder bed (z = -1 mm) at exposure time t = 0.023 s by finite difference method

Figure 5 shows the high-level degree temperature of PA12 is (172.2 °C), but at the bottom, the temperature is constant at 171 °C, while the temperature become constant (172 °C) at the center of powder bed.

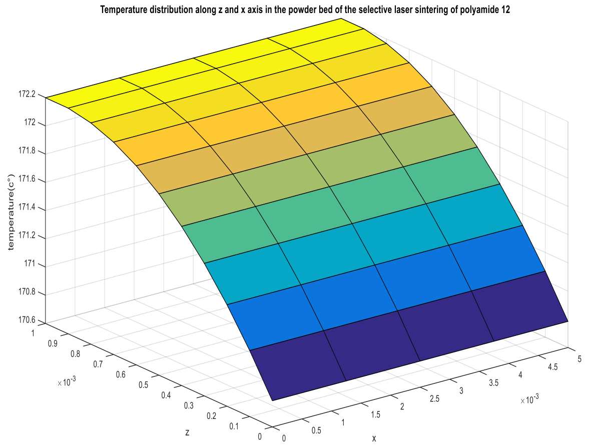

Figure 6. Temperature distribution along z and x-axis in the covering powder of the SLS of polyamide 12 at exposure time t = 0.023 s by finite difference method

Figure 6 shows the temperature along z and x, and the variable temperature is especially along z axes and a little constant along x-axes, the temperature along z is between 170.6 °C and 172.2 °C.

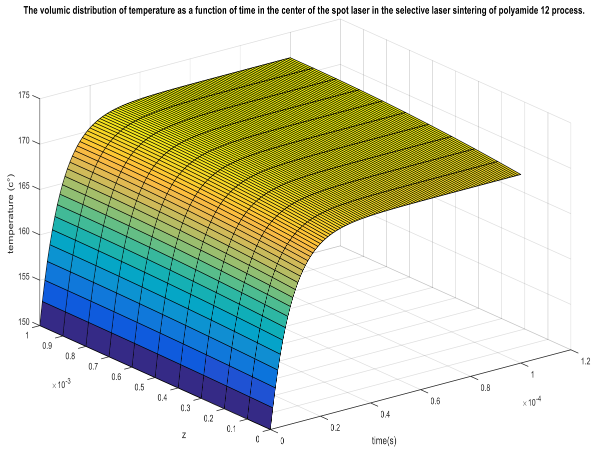

Figure 7. Temperature distribution along z and x-axis in the covering powder of SLS of Polyamide12

In this simulation, the maximum temperature is calculated in this point which is used as a reference point for the temperature gradient is in the center point of the fusion bed which is the maximum temperature. The Figure 7 shows the temperature evolution at the upper surface (z = 0) and along z at exposure time = 0.023 s and the variation temperature is especially along z axes and a constant along x axes and along y axes, the temperature after reaching the maximum temperature will remain constant.

4.2. Second Validation

For the second validation, the validation of our thermal model and our numerical simulation with experimental work [14] is chosen which we use the parameter in Table 2 and we measure the maximum temperature under the laser spot inside the selective laser sintering process.

The works of [14] shows the entry of the laser which applied in the surface on the powder bed. The laser scan passes over the long surface of the powder, and at the end of each scan a second layer has been added, and the scan is repeated until all four layers are sintered [14]. In our simulation only the first passage of the laser is taking into consideration, in the first layer of the Polyamide12 powder, which start between S and F and the time is about 0.00005 s [14].

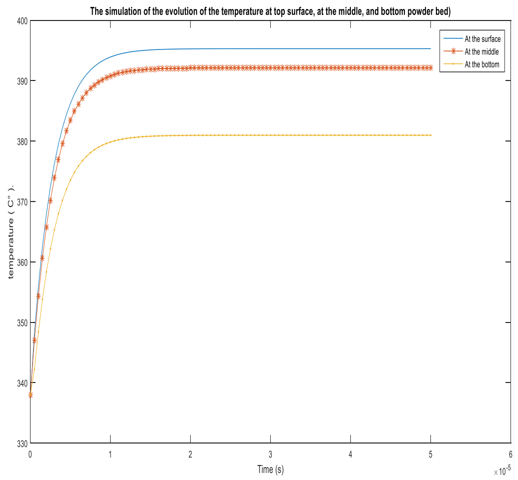

Figure 8. The simulation of the temperature at top surface (z = 0), at the middle (z = -0.5 mm), and bottom powder bed (z = -1 mm)) at 0.00005 s by finite difference method

The Figure 8 shows the numerical simulation of the laser projection of a layer of PVA powders using the parameters values in Table 2. Figure 8 shows the temperature evolution at the upper surface (z = 0), The temperature fields recorded at these points are close enough to be able to consider that we quickly reach the steady state, also high and restricted temperature reach 390 °C, seen while the entry of the laser source, The comparison of our result with the experimental work of the author [14], confirm the validation of our thermal model taking into consideration

The radiation and convection boundary conditions, which the maximal temperature in the surface of the spot of the first layer is exactly 395 °C, founded by experimentally work of the author [14] (Figures 9 and 10). In our simulation the maximum temperature was calculated, in the center point of the sintering pool.

The Figure 10 shows the temperature evolution at the upper surface (z = 0) and along z and x and y at exposure time= 0.00005 s of the laser in the middle of the spot laser On PVA powder inside the selective laser sintering process and variable temperature is especially along z axes and a constant along x-axes and along y-axes.

Table 2. Parameters of laser source and physical proprieties of PVA material used for the second validation

Thermo-physical properties	Full name	Value	Unit	Ref
K_e	Effective thermal conductivity	0.15	W/mK	[14]
T_0	Initial bed temperature	338	°C	[14]
Cp	Specific heat	1090	J/kg/K	[14]
σ	Stefan-Boltzmann coefficient	5.67×10^{-8}	W/m²/K⁴	[14]
$\in$	porosity	0.8		[14]
ρ	Initial density	1290	Kg/m³	[14]
h	Convection coefficient	15	J/cm²K	[14]
T_e	Temperature of the chamber	338	°C	[14]
P	Mean laser power	4	W	[14]
r	Laser beam Rayon	0.2e-3	m	[14]

The maximum temperature of PVA is (395 °C), at the bottom, the temperature is constant at 380 °C, while the temperature becomes constant (390 °C) at the center of the coat powder.

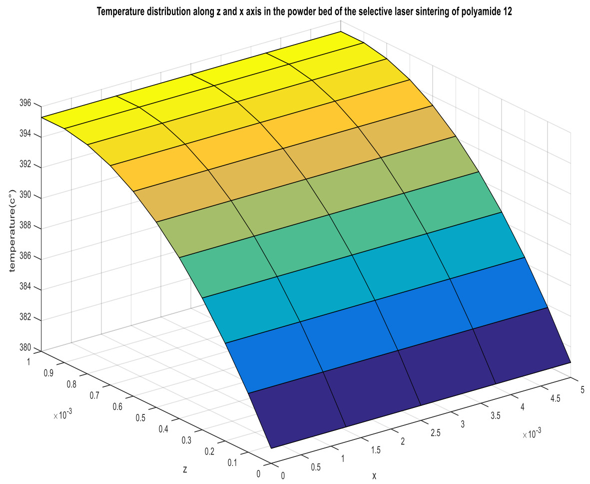

Figure 9. The volume distribution of temperature along z and x axis in the point focus under the spot laser in the selective laser sintering of PVA powder at 0.00005 s by finite difference method

The Figure 9 shows the temperature along z and x, and the variation temperature is especially along z axes and a little constant along x axes, the temperature along z is between 380° and 395.5 °C.

In the experimentally work of the author [14], the Figure 10 shows the passage of the laser which applied in the surface on the powder bed. This scan is repeated over the full scan of all layers is complete [14]. The simulation is run until all four powder layers are scanned.

The temperature solution is sampled as a function of time at the point in the domain which is the center of the x-y plane on the top surface of the initial layer of powder. The results are shown in Figure 10.

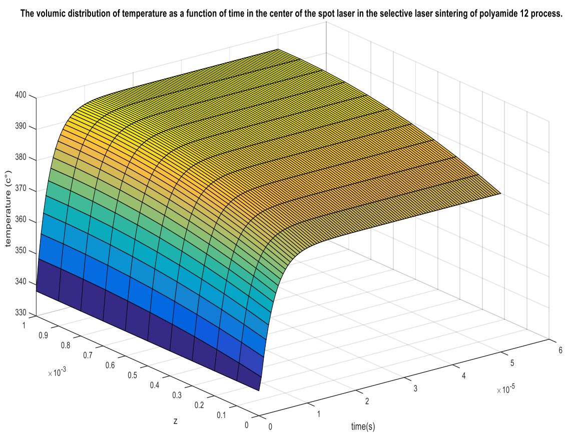

Figure 10. The volume distribution of temperature as a function of time in the center of the spot laser in the selective laser sintering of polyamide 12 process at 0.00005 s by finite difference method

Our simulation takes into consideration, only the first start of the passage of the laser, which the value of the maximal temperature is 395 °C at 0.00005 s, so using the same value of the physical proprieties of the material chosen by [14], and also the same parameter of the machine (Table 2). In this work, the same result has founded which the maximal temperature founded is 395 °C. Figure 10 shows (a) development of the temperature at the upper surface using the data of author [14] (z = 0), and (b) along z of the powder bed of PVA inside the SLS machine at 0.00005 s, the temperature after reaching the maximum temperature will remain constant.

4.3. Third Validation

In the literature, the analytical solution was proposed by the author [17] with the same thermal model with not taking into consideration the convection and radiation terms and is represented by the Equation (20).

$$T(z,t) = T_0 + 2\frac{\dot{q}''}{K}\left(\left(\frac{\alpha t}{\pi}\right)^{\frac{1}{2}} \exp\left(-\frac{z^2}{4\alpha t}\right) \right) - \frac{\dot{q}''}{K} z.\text{erfc}\left[\frac{z}{2(\alpha t)^{\frac{1}{2}}} \right] \quad (20)$$

Table 3. Parameters of laser source for the third validation

Thermo-physical properties	FULL NAME	Value	Unit	Ref
K_e	Effective thermal conductivity	0.23	W/mK	[30]
T_0	Initial bed temperature	150	°C	
C_p	Specific heat	1090	J/kg/K	[30]
σ	Stefan-Boltzmann coefficient	5.67×10^{-8}	W/m²/K⁴	[30]
$\in$	porosity	0.8		[30]
ρ	Initial density	1030	kg/m³	[30]
h	Convection coefficient	15	J/cm²K	[30]
T_e	Temperature of the chamber	150	°C	
P	Mean laser power	10	W	
r	Laser beam Rayon	3.5e-4	m	[32]

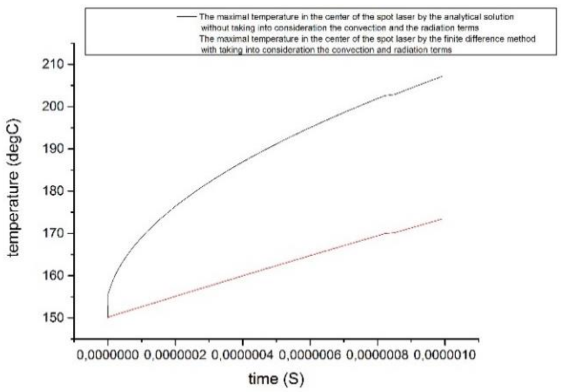

Figure 11. Comparison between analytical solution without taking into consideration the radiation and convection of the author Franco [17] and our finite difference method simulation

The Figure 11 shows the distribution of the temperature at the at the upper surface using the analytical solution, the maximal temperature equal to 210 °C. Comparing with our numerical solution by finite difference using the same data in the Table 3 which the maximal temperature equal to 175 °C but with consideration of radiation and convection terms, so the difference between two results is due to the heat losses by convection and radiation phenomena and this heat losses is about 35 °C.

Figure 11 shows a Comparison between analytical solutions without taking into consideration the radiation and convection of the author Franco [17] and our finite difference method simulation, The error between to result are: Error = (|210-175|/175|)×100, Error = 20%, so the error is due to the dissipation of temperature by the phenomenon of convection and radiation.

Figure 13 represent the distribution of the temperature at the upper surface using our numerical simulation by meshfree method, the maximal temperature equal to 177 C°. Comparing with our numerical solution by finite difference (Figure 12) using the same data in the Table 3 which the maximal temperature equal to 175 °C. So the difference between two results is just Error = (|177-175|/175|)×100, Error = 1.14%, and it's shows that a 3D meshfree method give us as always, a good result.

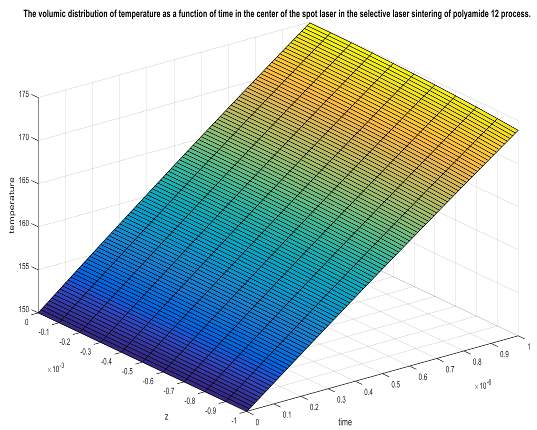

Figure 12. The volume distribution of temperature as a function of time in the point focus under the spot laser (in the center) in the selective

laser sintering of polyamide 12 process t_f = 0.000001 s by finite difference method

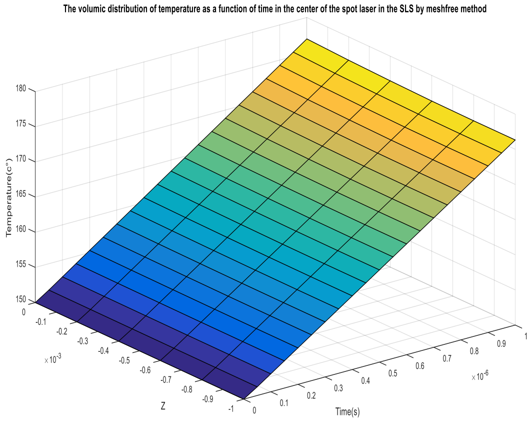

Figure 13. The volume distribution of temperature as a function of time in the center of the spot laser in the selective laser sintering of polyamide 12 process t_f = 0.000001 s by meshfree method

This numerical simulation also allows us to study the influence of machine parameters as P and D as well as the influence of physical properties like thermal conductivity and heat capacity, preheating temperature [36], [41], etc.

5. CONCLUSIONS

High-Temperature Laser Sintering machine is a powder bed fusion technique employed to manufacture polymers with high service temperature, usually above 150 °C. The aerospace, automotive, and medical industries have driven the demand for processing high-performance polymers, as they could offer a lighter and cheaper alternative while maintaining the mechanical and chemical performance required to replace metallic parts in particular environments. In this paper, a one and three-dimensional mathematical model solving by the finite difference method is programed to anticipate the heat fields inside a first a coat of Polyamide12 and other polyamides like PVA powder, and to calculate the maximal temperature in the center of the spot laser of the powder bed this problem is based on the solving of the equation of heat transfer with the consideration of the term describes convection as heat loss on the surface of the powder and including also the term of radiation which make the problem nonlinear and more difficult in the progradation.

The evolution of the temperature over time was calculated on the surface, After the laser beam has passed, the temperatures drop very quickly and become constant. All the values of maximal temperature in the covering polyamide of the laser spot of the major polyamide powder are between (174-184 °C), a comparison of the results was made with methodology calculation experimental results of the author [32] and [14], and also with the input data from [30] and comparing our result with other analytical solution proposed by franco [17] our model was approved and give a good result, and we validate the suggestion of the existent of convection and radiation phenomena inside of powder bed.

Also, a validation of our finite difference method simulation has been successfully done with our simulation by three-dimensional meshfree method that has been programed for the polyamide powder bed laser fusion process by Matlab software, in particular for SLS. The model considers Powder bed sintering process to analyze the heat transfer mechanism with the existence radiation and convection phenomena, it is clear that materials it is very apparent that the nature of the sintered part.

Three-dimensional mathematical model was developed to understand the heat transfer behavior in the SLS machine from the outcomes, it is very that the material properties and handle boundaries have a big role in the quality of the sintered part, and to test other different materials, to conclude a radiation and convection phenomena must be always taken into consideration in these thermal phenomena in the SLS process. This study facilitates after the study of Particle coalescence for different polymer materials used by the SLS machine. Therefore, thermal simulation plays an important role in improving material and process performance. The modeling showed a reasonable agreement with the methodology of which we can measure the parameters such as the energy density which is a key factor of the process, it allows a better understanding and optimization of this process. These simulations show the influence of the parameters used in this study in the SLS processing window, also these studies will be used to investigate ways to reduce the effects of high temperatures on polymer powders is presented.

REFERENCES

[1] L. Dong, A. Makradi, S. Ahzi, Y. Remond, X. Sun, "Simulation of the Densification of Semicrystalline Polymer Powders During the Selective Laser Sintering Process: Application to Nylon 12", Polymer Science Series A, Vol. 50, pp. 704-709, 2008.
[2] S. Dupin, "Fundamental Study of the Transformation of Polyamide 12 By Laser Sintering: Physicochemical Mechanisms and Microstructure / Property Relationships", Doctoral thesis, INSA Lyon, pp. 120-130, 2012.
[3] E. Dumoulin, "Additive Manufacturing of Parts in High Performance Thermoplastic Polymers and Polyamide 12 by the Selective Laser Sintering Process", Materials National School of Mines, Paris, pp. 10-15, Paris, 2014.
[4] D. Pham, K, Dotchev, W, Yusoff, "Deterioration of Polyamide Powder Properties in the Laser Sintering Process", Journal of Mechanical Engineering Science, No. 222, pp. 2163-2176, 2008.
[5] D. Rietzel, W. Aquite, D. Drummer, T. Osswald, "Polymer Powders for Selective Laser Sintering Production and Characterization", The 44th Conference on Manufacturing Systems, Madison (WI), pp. 13-20, 2011.
[6] D. Rietzel, M. Drexler, F. Kuhnlein, D. Drummer, "Influence of Temperature Fields on the Processing of Polymer Powders by Means of Laser and Mask Sintering Technology", International SFF Symposium an Additive Manufacturing Conference, pp. 14-18, Austin (TX), USA, 2011.

[7] M. Schmidt, D. Pohle, T. Rechtenwald, "Selective Laser Sintering of PEEK", CIRP Annals , Vol. 56, Issue 1, pp. 205-208, 2007.
[8] D. Kim, K. Choi, "Development and Performance Evaluation of Industrial 3D Real Object Duplication System by Selective Dual-Laser Sintering Process", International Congress on Applications of Lasers and Electro-Optics, pp. 15-19, Miami, FL, USA, 2005.
[9] L. Dong, A. Makradi, S. Ahzi, Y. Remond, "Finite Element Analysis of Temperature and Density Distributions in Selective Laser Sintering Process", Materials Science Forum, Vol. 553, pp. 75-80, 2007.
[10] A. Franco, L. Romoli, "Characterization of Laser Energy Consumption in Sintering of Polymer-Based Powders", Journal of Materials Processing Technology, Vol. 212, pp. 917-926, 2012.
[11] A. Tontowi, T. Childs, "Density Prediction of Crystalline Polymer Sintered Parts at Various Powder Bed Temperatures", Rapid Prototyping Journal, No. 7, pp. 180-184, 2001.
[12] L. Dong, A. Makradi, S. Ahzi, Y. Remond, "Three-Dimensional Transient Finite Element Analysis of the Selective Laser Sintering Process", Journal of Materials Processing Technology, Vol. 209, No. 2, pp. 700-706, 2009.
[13] D. Moser, "Multi-Scale Computational Modeling of Selective Laser Melting for Process Improvements", Doctoral Dissertation, Department of Mechanical Engineering, University of Texas at Austin, pp. 150-156, Austin, USA, 2017.
[14] D. Moser, S. Fish, J. Beaman, J. Murthy, "Multi-Layer Computational Modeling of Selective Laser Sintering Processes", ASME International Mechanical Engineering Congress and Exposition, Advanced Manufacturing, ASME, p. 20, Montreal, USA, 2014.
[15] C. Nelson, S. Xue, J. Barlow, "Model of the Selective Laser Sintering of Bisphenol-A Polycarbonate", Industrial & Engineering Chemistry Research, Vol. 32, Issue 10, pp. 2305-2317,1993.
[16] I. Roberts, A. Wang, R. Esterlein, M. Stanford, D. Mynors, "A Three-Dimensional Finite Element Analysis of the Temperature Field During Laser Melting of Metal Powders in Additive Layer Manufacturing", International Journal of Machine Tools and Manufacture, Vol. 49, Issue 12, pp. 916-923, 2009.
[17] A. Franco, M. Lanzetta, L. Romoli, "Experimental Analysis of Selective Laser Sintering of Polyamide Powders from Energetic Perspective", Journal of Cleaner Production, pp. 1722-1730, Italy, November 2010.
[18] X. Tian, G. Peng, "Process Prediction of Selective Laser Sintering Based on Heat Transfer Analysis for Polyamide Composite Powders", International Journal of Heat and Mass Transfer, p. 120, December 2017.
[19] M. Sun, J. Beaman, "Three-Dimensional Model for Selective Laser Sinterin", The 2nd Annual International Solid Freeform Fabrication Symposium, An Additive Manufacturing Conference Austin, pp. 102-109, Austin, USA, 1991.
[20] C. John, A. Steuben, A.P. Iliopoulos, G. Michopoulos, "Discrete Element Modeling of Particle-Based Additive Manufacturing Processes", Comput. Methods Appl. Mech. Eng., Vol. 305, pp. 537-561, 2016.
[21] A. Schmid, A. Amado, K. Wegener, "Polymer Powders for Selective Laser Sintering (SLS)", American Institute of Physics, Issue 1, Vol. 1664, May 2015.
[22] A. Papadatos, "Computer Simulation and Dynamic Control of the Selective Laser Sintering Process", M.Sc. Thesis, Clemson University, p. 7, Clemson, USA, 1998.
[23] D. Defauchy, "Simulation of the Direct Manufacturing Process of Thermoplastic Parts by Laser Powder Fusion", Doctoral Thesis, Arts and Crafts Paris-Tech., p. 120, 2013.
[24] A. Papadatos, "Computer Simulation and Dynamic Control of the Selective Laser Sintering Process", M.Sc. Thesis, Clemson University, pp. 120-140, Clemson, USA, 1998.
[25] H. Salem, H. Abouchadi, K. Elbikri, "Design for Additive Manufacturing" Journal of Theoretical and Applied Information Technology, Issue 10, Vol. 19, pp. 3-7, October 2020.
[26] X. Zong, J. Shi, X. Zhang, "Online Monitoring Based on Temperature Field Features and Prediction Model for Selective Laser Sintering Process", Applied Sciences, pp. 4-8, 2018.
[27] M. Vasquez, "Analysis and Development of New Materials for Polymer Laser Sintering", A Doctoral Thesis, Submitted in Partial Fulfillment of the Requirements for the Award of Doctor of Philosophy of Loughborough University, pp. 59-66, 2012.
[28] S. Zhou, F. Meng, Q. Feng, L. Dong, "A Spatial Sixth Order Finite Difference Scheme for Time Fractional Sub-Diffusion Equation with Variable Coefficient", IAENG International Journal of Applied Mathematics, Vol. 47, No. 2, pp. 175-181, 2017.
[29] A. Hussain, J. Alahyari, "Review of Polymers for Heat Exchanger Applications: Factors Concerning Thermal Conductivity", Applied Thermal Engineering, pp. 4-10, 2017.
[30] P. Peyre, Y. Rouchausse, D. Defauchy, G. Regnier, "Experimental and Numerical Analysis of the Selective Laser Sintering (SLS) of PA12 and PEEK Semi-Crystalline Polymers", Journal of Materials Processing Technology, Vol. 225, pp. 326-336, 2015.
[31] H. Zhou, J. Jeffrey, J. Derby, "Three-Dimensional Finite Element Analysis of Viscous Sintering", Journal of the American Ceramic Society, Vol. 81, pp. 533-540, 1998.
[32] O. Deshpande, A. Kulkarni, P. Patil, P. Nagare, "Design and Development of Experimental Setup for Polymer Selective Laser Sintering", World Congress on Engineering, p. 10, July 2019.
[33] R. Dayal, A. Jodhpur, "Numerical Modelling of Process Governing Selective Laser Sintering", Ph.D. Thesis, p. 11, Darmstadt, German, 2014.
[34] R. Brighenti, M.P. Cosma, L. Marsavina, A. Spagnoli M. Terzano, "Laser-Based Additively Manufactured Polymers: A Review on Processes and Mechanical Models", J. Mater. Sci., Vol. 56, pp. 961-998, 2021.
[35] H. Yaagoubi, H. Abouchadi, M.T. Janan, "Numerical Simulation of Heat Transfer in the Selective Laser

Sintering Process of Polyamide 12", Energy Reports, Vol. 7, Issue 2, pp. 189-199, November 2021.
[36] H. Yaagoubi, H Abouchadi, M.T. Janan "A One-Dimensional Meshfree-Method for Solving Thermal Problems of Selective Laser Sintering Process of Polymer Powders", The 5th International Conference on Optimization and Applications (ICOA), pp. 1-5, 2019.
[37] H. Yaagoubi, H. Abouchadi, M.T. Janan, "Review on The Modeling of the Laser Sintering Process for Polyamide12", E3S Web of Conferences, Vol. 234, p. 00006, 2021.
[38] H. Yaagoubi, H. Abouchadi, M.T. Janan, "Mathematical Modelling and Numerical Thermal Simulation of the Selective Laser Sintering Process of the Polyamide 12", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 49, Vol. 13, No. 4, pp. 162-169, December 2021.
[39] H. Yaagoubi, H. Abouchadi, M.T. Janan, "The Impact Study of Parameters and the Thermal Proprieties of the Polyamide 12 on the Temperature during the SLS Process", International Symposium on Advanced Electrical and Communication Technologies, p. 3, 2020.
[40] H. Yaagoubi, H. Abouchadi, M.T. Janan, "Mathematical Study on the Relation of Energy Density and Other Parameters in the Selective Laser Sintering of Polyamide12 and their Influences on the Quality of the Final Produced Part", The 6th International Conference on Optimization and Applications (ICOA), p. 4, 2020.
[41] H. Yaagoubi, H. Abouchadi, M.T. Janan, "A Three Dimensional Meshfree-Simulation Of The Selective Laser Sintering Process with Constant Thermal Coefficients Applied To Nylon 12 Powders", MATEC Web of Conference, p. 4, 2019.

BIOGRAPHIES

Hanane Yaagoubi was born in Morocco on April 24, 1992. She was at Nador Eljadida High School, Morocco between 2007 and 2009. She is a state engineer in mechanical design and innovation, FST FES, sidi Mohamed Ben Abdellah University, Fes, Morocco. She is currently a Ph.D. student at Laboratory of Applied Mechanics and Technologies (LAMAT), ENSAM, STIS, Research Center, Mohammed V University, Rabat, Morocco. Her research is focused on 3D printing, additive manufacturing, and here publications are more than 12 publications.

Hamid Abouchadi was born in Morocco. He was at Moulay Ismail High School, Meknes, Morocco between 1981 and 1982. He obtaining the Baccalaureate option "Mechanical Manufacturing", and doctoral degree in Manufacturing Processes from ENSAM (Cluny) and CRMR (le Creussot) in France Development of experimental tests for thermomechanical validation of the steel casting process which his doctoral thesis is in Applied Sciences. Metals, metallurgy. He aggregated in mechanical engineering from Rabat, Morocco. He is now a Professor of mechanical construction at ENSAM, Rabat Morocco. He supported his university accreditation in grade PH. His research focuses on mechanical manufacturing and mechanical construction, 3D printing, and his publications are more than 16 publications.

Mourad Taha Janan was born in Rabat, Morocco on January 6, 1960. He was at Hassan 2 High School, Beni Mellal, Morocco between 1971 and 1978. He has state engineering diploma (Master in engineering) in mechanical engineering from Mohammedia School of Engineering, Mohammed V University, Rabat, Morocco and state doctorate (Ph.D.) in applied sciences from the same university. He is the expert in education, technical and vocational training, numerical simulation in fluid mechanics. Now he is director in charge of Scientific Research and Cooperation in ENSAM, Rabat, Morocco. Her research is focused on fluid mechanics, renewable energies, 3D printing. He has more than 38 publications.