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MATHEMATICAL MODELLING AND NUMERICAL THERMAL SIMULATION OF THE SELECTIVE LASER SINTERING PROCESS OF THE POLYAMIDE 12

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Abstract- 3D printing is a very innovative technology for manufacturing three-dimensional polymer parts, like SLS printers which in particular use a CO_2 laser to fuse the polyamide particles, but the distinction of the temperature between the various parts of the process leads to the presence of distortions and deformations in the piece produced, therefore the aim of this work is the understanding of the whole process of laser sintering by the numerical simulation of the thermal model proposed by the meshless method while trying to continue the evolution of the temperature over time. here we considered constant physical properties such as constant thermal conductivity, constant heat capacity, a constant density, nonlinear problem takes into account the term of convection plus the heat source projection with the radiation phenomena. This article aims to understand the thermal phenomena which react within the laser sintering machine of PA12 by analyzing the evolution of the maximum temperature in the laser spot, and this does by modeling mathematics of this system which consists in solving the heat equations which have been solved by two different methods, the first is the meshless RBF method using MATLAB and is compared with our numerical simulation using the Comsol Multiphysics software, the result is satisfactory, and it's discuss the thermal conditions of the process and the relationship linking the influence of the parameters power while heating on the powder bed surface when heating the polyamide12 powder bed surface in order to optimize this high-tech process, our study is among the rare studies which takes into account the phenomenon of radiation and the problem become non-linear problem, Indeed, it was concluded that the numerical model seem very important to control the prediction. As a result, the temperature in the powder bed surface founded by RBF meshless method is very close to our simulation by the COMSOL software.

Keywords: Meshless Method, Thermal Analysis, Nonlinear, Heat Exchange, Selective Laser Sintering, Polyamide12.

1. INTRODUCTION

Selective laser sintering (SLS) is a promising method for producing three-dimensional polymer parts to meet the prerequisites of aerospace, automotive and biomedical companies [2]. Because of its light weight, its high quality, nylon12 widely used in different fields, including in the automotive and medical sectors [3]. And it's attracting more and more attention from researchers and companies. This technology is very modern but it is not yet a solid process for the manufacture of thermoplastics, given some deformation and warping that cause the quality of the final part to be lost, so that the SLS becomes reliable for thermoplastic materials, it is necessary even more effort to understand the physical phenomena associated with the procedure, demonstrate them in a useful way, establish a numerical simulation to reproduce the various stages of the procedure to improve the nature of the last parts.

The physical phenomena that describe the SLS process are diverse and very complex: the most important part for the study is the thermal exchange between the powder bed and the laser, in the majority of models of the latest work, including those who took into consideration the phenomenon of convection and the term of radiation, also others who neglected the term of radiation, on the other hand, the nature of the parts is based on a large number of process parameters and material: the preheating temperature, the ambient temperature of the chamber, the laser power, the diameter of the laser beam, the thickness of the layer, the thermal conductivity, the heat capacity, the density, the porosity of the powder layer, and so on, as no enterprise programming is accessible, the creation of a numerical code is essential to analyze the SLS process of a polymer powder.

Methodology surveys, and numerical or analytical simulations have been done by scientists who therefore believe that numerical simulations are a reasonable method for studying these problems. but are not approved their model experimentally. The selective laser sintering (SLS) technology has now become a doable innovation for making a complex part, [1-3]. Today several types of machines of this SLS process which use different materials such as PA12, PA6 and PEKK [25-29], the SLS machine has a high preheating temperature T_0, which comprises between the start of crystallization temperature (T_{cs}) with the start of melting temperature (T_{ms}). It is extremely low temperature (T_{cs}) along the time inside the facet powder bed cause thermal shrinkage in the phase of crystallization and the appearance of deformation of the layer, which is a defect in 3D printing.

In this article, the proposal for a thermal model of SLS will be numerically approved. Let us examine the development of the temperature with time on the surface of the polyamide 12 layer after the scanning of the CO_2 laser. By applying a method without RBF mesh, the results show that this technique invented in 1990 by Kansah, along history with very good results using this method. Based on previous studies [1-20] of the heat transfer modeling strategy in the sintering laser, the conventional Fourier thermal displacement conditions are better known for temperature dispersion.

Taking into account the Fourier condition, different models have been created by thermal analysis of the non-linearity of the thermal properties of the material, the appropriation of the laser heat source and the collaboration among a laser and a powder bed [21-27]. One of these models can be fully understood scientifically, numerical simulations are used to measure the temperature within the powder bed to fully understand its distribution, Incredible efforts have been made in the thermal analysis side of SLS, but there are still many sides of progress to be made like mechanical analysis.

Analytical and numerical modeling as in a better simulation understanding of the SLS heat flux, which included a lot of parameters [32-42] laser power, energy density and the proportion of material retention, and thermal properties, for example, thermal conductivity, powder thickness during laser sintering, are required. From the literature of various numerical thermal SLS models, one tends to see that some models attempt to talk about parts in length scales similar to those actually worked in SLS. This is because the problem is exceptionally and nonlinear, resulting in overwhelming computational weight. In the perspective work that carefully chooses an effective digital strategy and uses some type of versatile cross-cutting innovation will be of extraordinary help.

With the advancement of digital demonstration [42, 43], streamlining the limits of the procedure and studying the exact connection between the limits of the process and temperature set off simpler. These models could then be approved using all-around temperature estimation frames created. Later, a parametric SLS reconstruction model that accurately predicts ideal procedure boundaries or boundary windows will fundamentally benefit customers from advances in laser sintering.

1.1. Physical Phenomena

The laser sintering process highlights thermal phenomena shown diagrammatically in Figure 1.

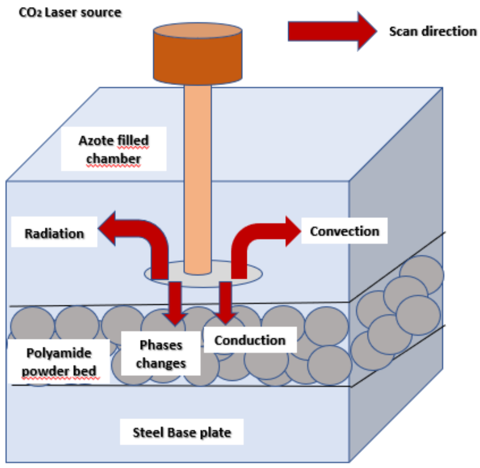


Figure 1. Physical conditions in SLS [39]

The Figure 1 represents the construction of polyamide12 on a steel substrate, The process parameters and the thermal properties of polyamide12 are taken from [11]. The material is PA12 , the parameters of the model and the process are presented in Tables 1 and 2. The simulation is carried out in MATLAB by meshless method and the same simulation by COMSOL software multiphasic, The laser beam is supposed to have a surface distribution with a spot size of 120 μm. Convective heat and radiation in the molten pool are not neglected compared to the studies of the author studies [31], and the initial temperature is fixed at 130 °C [25-26], this is the value of the preheating temperature already used also in several studies like [9] and [10].

1.2. Thermal Modelling of SLS Process

To achieve our goal of thermal modelling, the further development of the surface temperature of PA12 powder bed is over time is necessary. Transient heat transfer conditions are composed according to the following hypotheses [9] [11] [12] [18]:

- The Figure 1 describes the thermal history shown inside the powder bed, considering a surface heat dissipation and considering convection and radiation as heat losses.
- The bed of polyamide powder was thought to be homogeneous and consistent [9].
- Measuring the temperature of the powder bed surface under the laser spot.
- The physical properties of the materials considered constants.
- The thermal conductivity depends on the porosity.
- Non-linearities due to heat capacity of the material dependance of temperature and assuming constant density and thermal conductivity.

The objective of this simulation is to calculate a maximum temperature at the facet of the polyamide powder bed of the polyamide 12 during the SLS, however there are a lot of theoretical model and experimental study who calculated this value [9].

2. THERMAL MODEL AND NUMERICAL SIMULATION USING RBF MESHFREE METHOD

2.1. Heat Transfer Equation

The technique of the SLS was modelled in several methods and dimensions (1D to 3D) by past works dealing with polymers [4-6]. The phenomenon is described by the most not unusual the only dimension heat conduction, it's solved numerically with heat loss of the natural convection with radiation, with the symbols and values in Table 1.

The problem is based on solving the heat transfer inside the powder bed is represented by enthalpy equation [25]:

$$\frac{\partial H}{\partial t} = \nabla.\left(\frac{K_e}{C_p \rho}\nabla \mathrm{T}\right) + f(z,t) \quad (1)$$

where, $H(z,t)$ is the total enthalpy of the powder bed under pressure p, $T(z,t)$ is the temperature, K_e is the thermal conductivity, and $f(z,t)$ is the heat source.

Equation (1) is describing a conservation of enthalpy and along the z axis, the farther the point is from the surface, the less energy it gets from the laser and the z axis should be pointing downward into the powder bed.

- The Initial Conditions

The bed of powder is first preheated to an initial temperature of 130 °C; for $t = 0s$ $T(x,y,z,0) = 130$ °C (Pre-heating temperature).

- Boundary Conditions

Convective and radiation boundary condition sets how heat is transferred from the environment (denoted as T_∞) to the boundary volume as shown:

We have imposed in the boundary conditions the convection and the radiation fluxes on the surface of the nylon powder along the z axis:

$$-K_e \frac{\partial T}{\partial Z} = h\left(T_e - T_z\right) + \sigma \int \left(T_e^4 - T_z^4\right) \quad (2)$$

No dissipation of heat flux at the bottom:

$$-K_e \frac{\partial T}{\partial Z} = 0 \quad (3)$$

- Laser Source Model

In the other works, there are several formulations of the laser source distribution on the surface of the powder bed, the model chosen is as Table 2, where, P and r are the parameters of the laser source which is described like as input energy during the SLS process, in this study, q_0 [W/m²] is the specific thermal power of the laser radiation determined by Equation (4), being P and r are the power and the spot rayon of laser spot size [25]:

$$q = \frac{P}{\pi r^2} \quad (4)$$

The material chosen for our study is nylon12(PA12), where the physical properties were considered constants, (Table 1).

Table 1. Parameters of laser source [4]

Process Parameter	Full Name	Value	Unit
P	Mean laser power (W)	1.8	W
r	Laser beam radius at 1/e²	1.2e-4	m

Table 2. The thermophysical properties data of polyamide12 [25-27] and temperature measurements were determined by DSC experiments detailed in [25]

Thermo-Physical Properties	Full Name	Value	Unit	Reference
K_e	Effective thermal conductivity	0.23	w/mK	[11]
T_0	Preheating bed temperature	130	°C	[11]
C_p	Specific heat	1090	J/kg/K	[11]
σ	the Stefan-Boltzmann constant	5.67×10^8		[11]
ε	the thermal radiation coefficient	0.8		[11]
ρ	Initial density	1030	kg/m^3	[11]
h	Convection coefficient	15	J/cm²k	[11]
T_s	Temperature of the powder bed surface	to calculate	°C	
T_e	Temperature of the chamber	130	°C	[11]

2.2. Numerical Simulation of the Meshfree Method

2.2.1. RBF Apply

Solving this heat transfer equation is done by Multi-Quadric (MQ) method (Figure 2). The $\hat{T}$ is approximate solution of T, and also is a multi-radial Basic Radial Function (RBF), since this equation admits only one solution, then [4]:

$$\hat{T} = \sum_{j=1}^{N} \alpha_j(t) \times g_j(z - z_j) \quad (5)$$

The Hardy Multiquadric is

$$G(r) = \sqrt{r^2 + c^2} \quad (6)$$

$$g_j(\| z - z_j \|) = \sqrt{\left(z - z_j\right)^2 + c^2} \quad (7)$$

Let us use the decentered formula before approximating the derivative of T with respect to t. Which gives us [4]:

$$\frac{T^{n+1} - T^n}{\Delta t} = r \times \sum_{j=1}^{N} \alpha_j(t_n) \times \frac{\partial^2 g_j(\| z - z_j \|)}{\partial^2 z} \quad (8)$$

Now, the calculation of the second derivative of T with respect to z gives us:

$$\frac{\partial T^2}{\partial Z^2} = \sum_{j=1}^{N} \alpha_j(t_n) \times \frac{\left(z - z_j\right)^2}{\left(\left(z - z_j\right)^2 + c^2\right)^{3/2}} \quad (9)$$

Thus, the Fourier equation becomes:

$$\frac{T^{n+1} - T^n}{\Delta t} = r \times \sum_{j=1}^{N} \alpha_j(t_n) \times \frac{\partial^2 g_j(\| z - z_j \|)}{\partial^2 z} \quad (10)$$

The evaluative matrix system of this equation is [4]:

$$U^{n+1} = U^{n} + \Delta t \times r \times A\alpha^{n} \tag{11}$$

where,

$$A(i,j) = \frac{c^2}{\left(\left(z - z_j\right)^2 + c^2\right)^{3/2}} \tag{12}$$

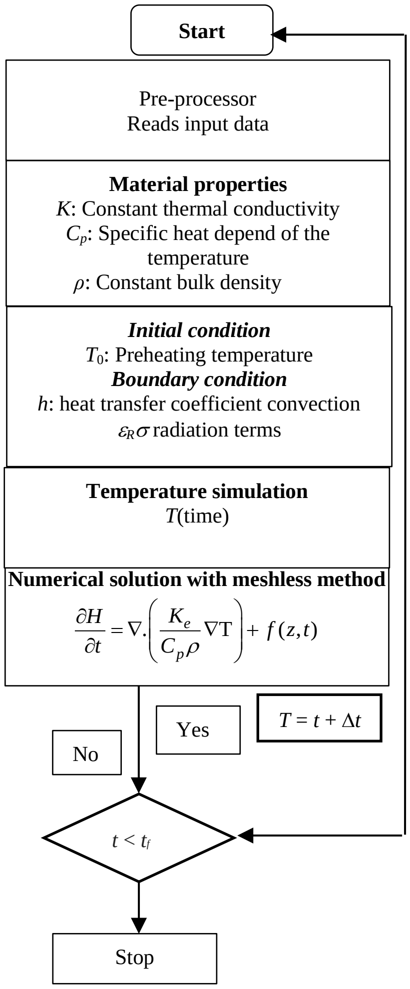


Figure 2. General flow chart of thermal numerical simulation by the meshless method using MATLAB environment

3. SECOND NUMERICAL SIMULATION BY COMSOL MULTIPHYSICS SOFTWARE

The SLS process is based on the laser projection of polyamide powders in a substrate [1-2], it is accompanied in particular by state change phenomena (melting and solidification of the material). The significant thermal gradients observed during the process are the cause of the appearance of residual stresses in the parts. The objective of our study is to develop a numerical simulation of the deposition of a polyamide12 layer on a substrate from the thermal modelling induced by the process using the COMSOL Multiphysics software.

Using COMSOL Multiphysics TM 5.3 software, making a 3D numerical simulation in thermal module [42]. The meshed volume (considered for the thermal simulation was a 5 mm × 4 mm × 1 mm (Figure 3, Table 4), Linear hexahedral elements were considered, with a mesh refinement in laser path (Figure 4). The heat equation was numerically solved in transient conditions (Equation (13)).

The model simulates a polyamide 12 first layer (Figures 3 and 5). The temperature analyses in the first layer are shown in Figure 9. The maximum temperature at the spot laser, as such, the laser will heat the layer, in Figures 7 and 9, illustrates the moment when the laser beam is projected and we can see that the temperature of occurs after the passage of the beam.

3.1. Polyamide 12-Layer Modeling

The same thermal model used in the numerical simulation by RBF meshless method have been used in this second simulation by finite element under COMSOL software but in 3D dimensions.

$$\frac{\partial T}{\partial t} = \frac{K_e}{C_p \times \rho}\left(\frac{\partial T^2}{\partial x^2} + \frac{\partial T^2}{\partial y^2} + \frac{\partial T^2}{\partial z^2}\right) + Q_V \tag{13}$$

- *The Initial Conditions*

The bed of powder is first preheated to an initial temperature of 130 °C; for $t = 0s$, $T(x, y, z, 0) = 130$ °C (Preheating temperature).

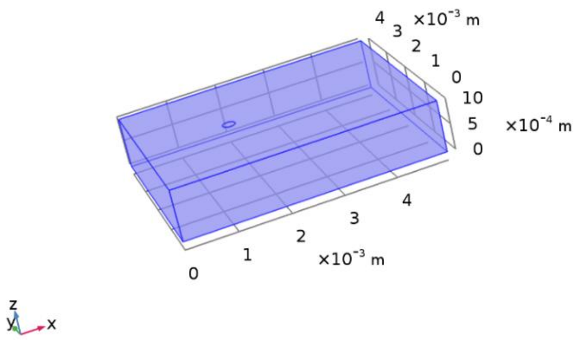


Figure 3. Sizing of the polyamide12 layer

- *Boundary Conditions*

Convective and radiation boundary condition sets how heat is transferred from the environment to the boundary volume, as shown:

We have imposed in the boundary conditions the convection fluxes and the radiation on the surface of the nylon 12 powder along the *z* axis [25]:

$$-K_e \frac{\partial T}{\partial Z} = h\left(T_e - T_z\right) + \sigma\int\left(T_e^{4} - T_z^{4}\right) \tag{14}$$

No dissipation of heat flux at the bottom [25]:

$$-K_e \frac{\partial T}{\partial Z} = 0 \tag{15}$$

where, T_s is the temperature of the powder bed surface, T_{ext} is the temperature of preheating (373 K for PA12, h is the natural convection coefficient at powder bed surface h = 15 W/m-2/K-2, ε_R is the surface emissivity assumed to be equal to 0.8 considering pyrometer data, σ is the Stefan Boltzmann coefficient (5.67e-8 W/m-2/K-2).

The heat input due to the presence of the laser is often modelled in the literature by a surface flux of a density of distribution [6]. This density of the flow is written in the form (16):

$$q = \frac{P}{\pi r^2} \tag{16}$$

Table 3. Process parameters

Name	Designation	Expression	Value
L	Length	5 [mm]	0.005 m
l	Width	4 [mm]	0.004 m
H	Height	1 [mm]	0.001 m
R_{ls}	Spot Laser Radius	120 [µm)]	1.2E-4 m
P	Laser Power	1.8 [w]	

Table 4. Mesh data

Description	Value
Minimum element quality	0.2095
Average quality of elements	0.6744
Tetrahedron	16415
Triangle	2130
Edge element	164
Point element	12

Table 5. Settings

Description	Value
Maximum element size	2.75E-4
Minimum element size	2.0E-5
Curvature factor	0.4
Resolution of thin regions	0.7
Maximum Element Growth Rate	1.4
Preset size	Thinner

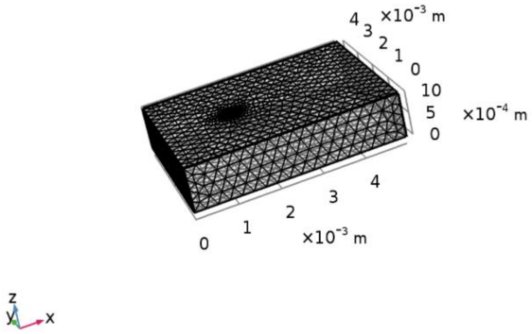


Figure 4. Domain mesh

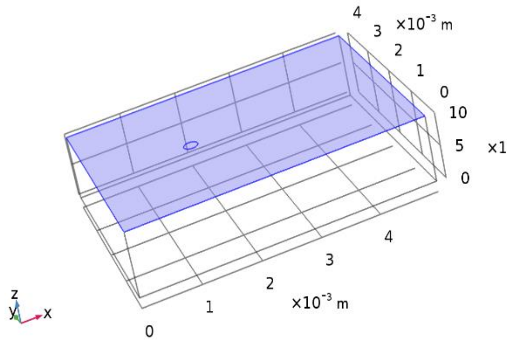


Figure 5. Selection of heat flow 1 on the surface of powder bed

The simulation of the spot laser on the nylon powder layer has been done. Figure 6 shows the development of the temperature in the powder layer. it's observed that the high temperatures sett of the liquidus temperature (175 °C) of nylon12. And this extreme temperature is due because of the minimum rayon of laser used.

The final part produced. The residual stresses developed during laser deposition therefore originate from thermal deformations on the one hand and mechanical boundary conditions.

4. RESULT AND COMPARISON

4.1. First Case

Thermal Simulation of powder bed of polyamide12 in SLS process with Constant Flux by meshless method using MATLAB software & EF method using COMSOL software.

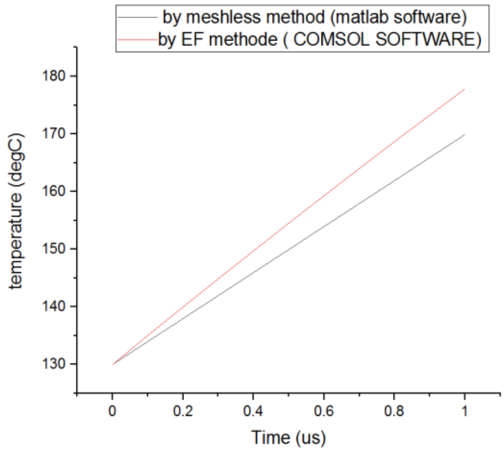


Figure 6. Comparison of the evolution of the temperature on a facet of powder of polyamide 12 for 1 µs by meshless method (MATLAB) and EF method by COMSOL software simulation.

Using the same parameter in Tables 1 and 2, and this logical data in the machine SLS from author [11] , this is the evolution of the maximum temperature in the laser spot, and this does so by modeling mathematics of this system which consists in solving the heat equations which have been solved by two different methods, the first the RBF meshless method and also with a numerical simulation using the COMSOL Multiphysics software (Tables 4 and 5), As a result, the temperature in the powder bed surface found by meshless method is very close to our simulation by the COMSOL software. we detected exact time that the temperature reaches the melting temperature of the powder in 170 °C in the laser flux constant, and our code of meshless method has been validated.

4.2. Second Case

Thermal Simulation of the powder bed of polyamide 12 in the SLS process with variation Flux by COMSOL Multiphysics software (Figure 7).

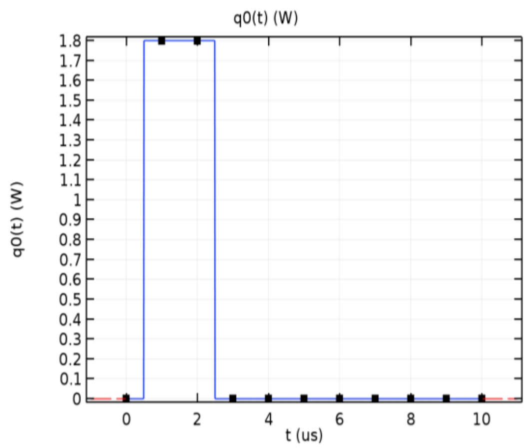
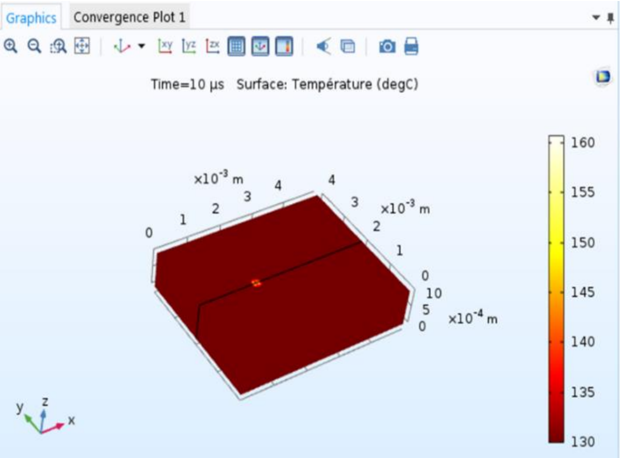


Figure 7. Interpolation of the function $q_0(t)$



Temps=10 µs Surface: Temperature (°C)

Figure 8. Temperature variation over time within the surface of the laser spot on the surface of the polyamide 12 powder bed

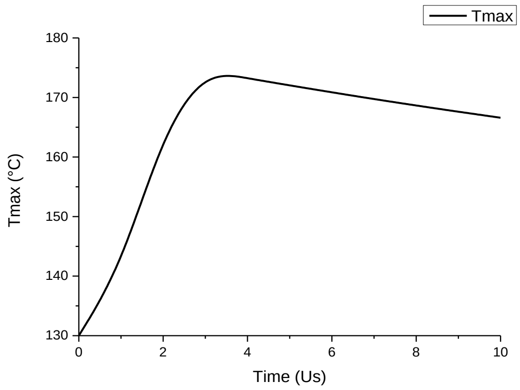


Figure 9. Temperature evolution within the surface of the laser spot on the surface of the polyamide 12 powder bed. (Thermal simulation (PA12 powder, T_0 = 130 °C, $q_0(t)$) in 10 µs.

In our result (Figures 8 and 9) we conclude that the variation of the power of laser affect the length of time of the melting temperature.

5. CONCLUSION

In this study, a numerical model was developed, based on the heat equation, taking into account conduction, convection, radiation phenomena linked to the sintering of polyamide12 allowing to simulate the SLS process. This model was validated by means of evaluating the effects of the numerical simulation of the deposition of a layer of polyamide powders on a substrate with RBF meshless method under MATLAB Software and numerical simulation by COMSOL software, The use of this models must continue to optimize the process in the case of multilayer deposits.

A logical values parameters of the SLS machine was used as input of the model taken from the bibliography can help us to detect the exact time that the temperature reaches the melting temperature of the powder in 170 °C in both cases first for a laser flux constant and a second for a variable flux, so also it's concluded that the term of radiation can be neglected because it has no influence on the result and is due to small exchange area, and that's confirmed the hypotheses of the other authors, like author Franco and Denis. Finally, the more important is that our algorithm code using RBF meshless method is adaptative algorithm which give us a good result comparing to our analyse by finite element using COMSOL software, this study shows the advantages of these meshfree method which is simple and efficacies compared to current, expensive commercial codes for doing complex analysis, and will help us to control all the parameters influenced on the quality of the final powder bed of PA12 inside the SLS Machine.

NOMENCLATURES

1. Acronyms

RBF Radial basis function
CO_2 Laser CO_2
MJF Multi Jet Fusion
DSC Differential Scanning Calorimetry
PA12 Polyamide 12
SLS Selective Laser Sintering

2. Symbols / Parameters

T_0 Initial bed temperature
K_e Effective thermal conductivity
C_p Specific heat
ρ Initial density
Q_V Heat source
h Convection coefficient
T_S The temperature of the facet of powder bed
T_e Temperature inside the machine
T_g Glass Transition Temperature
T_m Melting Temperature

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