Experimental Analysis of Selective Laser Sintering of Polyamide Powders from Energetic Perspective

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Abstract

The diffusion of innovative working process, including rapid prototyping techniques, is needed to achieve sustainable production technology. Selective Laser Sintering (SLS) has a potential as an environmental benign alternative to traditional processes but only few authors deal with the process optimisation including energy aspects. In the present paper an analysis of the energetic aspect of SLS is proposed. In addition, with respect to the classical technological parameters (resolution, productivity) attention is paid to energetic elements (energetic productivity, laser parameters) showing how the perspective of a sensible development of such a kind of technology could be beneficial not only from a technological point of view, but also for energy saving in a lot of manufacturing fields. A polyamide powder is the material tested to acquire some characteristics data of the process. It is shown that the energy intensity of the process in optimal condition could be of the order of 0.2 J for each mm^3 of material agglomerated.

Keywords:

Rapid Prototyping, Selective Laser Sintering, Multi-objective optimisation, Modelling, Energy intensity, Energy saving

The manuscript is of about 6300 words including abstract, references and captions.

NOMENCLATURE

abs	absorption coefficient	
c_p	specific heat	J / kg K
k	thermal conductivity	W / m K
P	power of laser beam	W
$\dot{q}''$	specific thermal power of the laser radiation	W/m^2
Q	intensity of line heat source	J/m
r	cylindrical coordinate	m
ref	reflection coefficient	
s	distance traveled in the unit time	mm
t	time	s
t*	radiation incidence duration	s
tr	transmission coefficient	
T(z)	temperature in the z direction	K
T_g	glass transition temperature	K
T_o	initial temperature of the powder bed	K
V	scanning speed	mm/s
VP	volumetric productivity	mm^3/s
VEI	volumetric energy intensity	J/mm^3
z	coordinate in the direction of the laser beam	m
α	thermal diffusivity (= k / ρ c_p)	m^2 / s
Ø	spot diameter of laser beam	µm
ρ	density	kg/m^3

1. Introduction

The purpose of manufacturing processes is to transform materials into useful products. In the course of these operations, energy resources are consumed. Much of the work characterizing environmental impacts of manufacturing processes and systems has focused on energy consumption patterns. From the analysis of the literature it is apparent that energy and electricity use per unit volume (or mass) of material processed has increased over the past decades [1, 2]. Energy consumption is a component of environmental impact and it is a critical component in any overall sustainability strategy [3].

For this purpose Rapid Prototyping techniques offer advantages in terms of energy consumptions reduction since they are based on the concept of fabricating a predefined object by material deposition instead of the conventional chip removal mechanisms.

Of all RP techniques, Selective Laser Sintering (SLS) seems to be one of the most consolidated processes to create solid objects, layer by layer, from plastic, metal, ceramic powders or pre-coated sands that are sintered using laser energy [4]. SLS not only reduces the time and cost of prototyping components, obtaining the same dimensional accuracy, surface finish and repeatability as common manufacturing process, but also reduces the energy intensity and the environmental impacts of the process.

The basic concept, common to all rapid prototyping techniques, is that any complex shape can be produced by the superposition of small thickness layers. In case of SLS, layers of 0.05–0.3 mm thickness are obtained by thermal binding of small particles that are agglomerated together by the action of a laser source whose wavelength depends of the powder adopted. A CAD software is commonly used to decompose a 3D drawing into a sequence of thin layers whose shape is used to set the working area of the laser beam. After a layer is sintered at a predefined focal length, new uncured powder is levelled on a platform whose vertical adjustment (governed by a step-motor) allows re-focusing of the laser beam.

The inherent versatility of SLS technology combined with a large variety of powder materials allows a broad range of advanced rapid prototyping and manufacturing applications. As a matter of fact, the powder consolidation mechanisms depend on the nature of the material used and on the mechanical properties to be obtained (e.g. porosity) as reported by Kruth et al. [5]:

- Solid State Sintering is a consolidation process occurring below the material's melting temperature and governs the agglomeration of most ceramic and metallic powders;

- Liquid Phase Sintering is common for mixture of two-components powder, composite powder particles and coated particles;

- Partial Melting can be adopted for metals and for polymers under the threshold value represented by the glass transition temperature;

- Full Melting is a third major consolidation mechanism often applied to metals to achieve fully dense parts;

- Chemical Induced Binding is also possible for polymers, metals and ceramics even though not commonly used in commercial applications.

As reviewed by Kandis et al. [6], polymers are the most processed type of powders in SLS but the consolidation phenomena related to these materials seem to be the most complex among all those described in literature. They concern a deep interaction between heat, mass and momentum transfer as well as chemical modifications of the

materials and variation of mechanical and thermophysical properties. This hinders a comprehensive treatment of the physical phenomena of grain agglomeration and makes the analysis of the process very complex. As a direct consequence, even if a wide range of amorphous and semi-crystalline thermoplastics have been experimentally tested for the SLS process, commercial applications today are limited to a small number of thermoplastic polymers: mainly polyamide (PA 12 and PA 11), polycarbonate (PC), polystyrene (PS), Polyether-etherketone (PEEK) and variants of those. Polymers are characterised by quite low sintering temperature (< 200 °C) and thermal conductivity (below 1 W/m K) so that they can be considered as insulating materials. Polymer powders have a peculiar behaviour with respect to a heat transfer dominated process like SLS and differs from the case of metal based powders which are characterised by thermal conductivity and thermal diffusivity of one or two orders of magnitude higher.

The application of SLS is often based on empirical and technological experience especially for polymers whose thermophysical properties are covered by industrial patents. In these cases, one of the main problems concerned with the application of the SLS technology is the selection of optimal parameters. For a given kind of polymer powder, the selection of optimal parameters firstly needs the definition of thermophysical properties like density, specific heat, thermal conductivity, glass transition and melting temperature and other properties, such as granulometry and average grain dimension. Secondly the influence of the main technological parameters such as

- average power

- spot diameter

- scan speed

on the sintering process of single lines has to be investigated in order to guarantee a reliable adhesion between grains, allowing a suitable depth of penetration, which determines process resolution. Flat surface could then be obtained by spacing multiple straight sintered lines at an appropriate fixed step (scan spacing parameter), which depends on the width of a sintered line. This can guarantee a correct superposition of several layers without distortions.

For this purpose, a model of the process can be important to understand how the various process variables (parameters) affect the sintering mechanisms in order to select appropriate parameters values before processing and provide guidelines for optimization of the process both from technological and energetic point of view.

Several papers are available that consider the process of Selective Laser Sintering from the modelling perspective. An energy balance model for polyamide [7] and an analytical model for polycarbonate have been proposed in [8] and [9]. Three strategies have been investigated: analytical, adaptive mesh finite difference and fixed mesh finite element, with more layers. The aim of the simulation was to predict the sintering depth/width as a function of the process parameters. The authors proposed a one-dimensional analytical model [10] and a 3D numerical model [11] of the SLS process of pre-coated sands for shell-moulding. In [12] a purely experimental (DOE) approach is used to evaluate the mechanical resistance of a polymer composite as a function of the Energy density. While [13] optimises the SLS parameters to build polyester lattice structures. Also experimentally, [14] and [15] examine the effect of preheating and respectively of part porosity and post-processing on the mechanical properties of polyether and polycarbonate. Although complex and impractical, two- and three-dimensional analytical models still show severe limitations for direct quantitative predictions. Numerical models still require a deep understanding of the most involved phenomena. Thermo-physical properties of the materials need to be characterised with special tests and methods [16] as well as the effective

energy input: these critical issues represent a serious drawback which strongly limits the implementation of such models. On the other hand, purely experimental (statistical) approaches are necessarily specific, they are not able to seize the phenomenal aspects and they may turn out to be inefficient. Only a few optimisation examples are available in the literature, particularly in the case of polymer based powder beds. RP techniques were conceived for time compression. With growing energy constraints, SLS has the potential of saving direct and indirect materials, energy, emissions, money etc. compared to conventional processes [17]. Only few examples of energy consumption and other environmental impact parameters for different RP processes [18] showing the advantage of laser based metal deposition versus conventional processes [19] are available in the literature. Manufacturing is directly connected to natural resources and energy use. This dependence results in a necessity to reduce the amount of employed resources, with increasing product output, and thereby increase resource productivity and energy requirements.

The main purpose of this work is to develop and enhance the knowledge regarding the energetic aspect of SLS of common polymer powders. The first step will represent the analysis of the SLS process that includes productivity and energy aspects and simple process modelling for preliminary parameter estimation. For this purpose a standard version of the process, that cannot be referred to any specific industrial version, and without preheating has been considered.

In addition it will point out the thermo-physical properties, such as the thermal conductivity and diffusivity, which represent key parameters in the SLS of polymer powders.

As final step of the research, sintering will be carried out to fabricate single lines on uncured layers of DuraForm[TM] Polyamide powder in order to assess if the process modelling can be useful to obtain some preliminary information of the energy requirements. This type of powder was chosen firstly because of its common use and secondly for its thermophysical properties which are comparable to many other amorphous (PS, PMMA, PC) or semi-crystalline (PE) thermoplastics.

The energy consumption discussed in this paper is limited to the theoretical optimal process energy which is also just a part of the total consumed energy of a manufacturing process. The rather low efficiency of the laser source as well as the energy consumption of auxiliary energy consumers (e.g. drives, servos, pumps of process gasses, exhaust units, cooling, pc, .) in productive and non-productive modes, ensure that the necessary practical energy consumption is significantly higher for this type of processes. During an environmental or energy based comparison of different manufacturing processes, it is consequently more relevant to take these practical (complete) consumptions into account. A relevant paper about the energy requirements of manufacturing processes could be found in [20]:

2. Modelling of the SLS process

SLS is characterised by a deep interaction between heat, mass and momentum transfer along with chemical transitions and variations of the mechanical and thermophysical properties of the materials. According to the optimisation method outlined in figure 1, models can be used to estimate preliminarily the process parameters testing range. This indicates the necessity of development of simple phenomenological models.

HERE FIGURE 1

In this paper the attention is primarily focused on the energetic aspects of the process and it is assumed that the SLS of polymer based powders is dominated by heat transfer and the models are based on the following hypotheses.

- A complete thermal model should include the terms shown in Figure 2, but convection and radiation at the boundary are negligible because of the small exchange surface and low temperature.

- Sintering is observed mostly when the radiating energy is acting [10].

- The variations of the thermo-physical properties of the material, particularly of the thermal conductivity and of the specific heat, are averaged within the observed temperature range.

- The material is considered continuous and homogenous with isotropic thermal conductivity.

- Local phenomena related to chemical reactions that could be important are not considered.

- Energy consumption related to pre-heating can be considered necessary for keeping certain boundary conditions of the Fourier equation and therefore does not take part in optimization of the laser parameters. This hypothesis will be recalled during the discussion of the experimental results.

The mathematical description involves the solution of the *unsteady* heat conduction equation. The model reproduces the thermal history within the powder bed when the incident radiation is scanned over it.

There are several analytical solutions that can be useful for the calculation of the transient temperature and of the heat transfer of objects irradiated by a power input [21].

HERE FIGURE 2

When the laser spot hits the powder, the surface interaction with the radiant energy can be described by the coefficients representing the fraction of absorbed abs, reflected ref, and transmitted energy tr (figure 2), which must sum to unity i.e.

$$abs + ref + tr = 1 \tag{1}$$

The three coefficients depend on the powder used. For a generic polyamide powder, the absorption coefficient, abs, is sensibly higher than 0.9. As mentioned earlier, the penetration of the glass-transition temperature front into the powder bed determines the depth and width of the heat-affected zone (HAZ). However this thermal problem, even if conceptually simple, has no simple solution for the following reasons:

- the intrinsic complexity of the phenomenon and its mathematical modelling (three-dimensional thermal conduction with convective surface heat dissipation);

- the difficulties in the characterization of the material from a thermo-physical point of view (thermal conductivity, specific heat capacity and thermal diffusivity);

- the difficulties in a correct modelling of the material from a chemical point of view (polymerization temperature, energy released during the polymerization process caused by the breakage of chemical links, melting, etc.).

Moreover it would be necessary to consider the following aspects that are usually neglected in the modelling:

- the influence of mechanical phenomena, like the powder agglomeration caused by friction and by special thermo-hygrometric conditions;

- the effects of non-homogeneous material;

- the changes of thermo-physical properties of the material with temperature.

The modelling of the process has been performed in various forms (from one to three dimensions) by most authors dealing with polymers [7] [8] [9]. The heat transfer in a plane perpendicular to the laser axis is neglected and the heat transfer, dominated by conduction, is only studied in the laser beam direction (z in Figure 2). The phenomenon is governed by the following one-dimensional heat conduction equation, with the symbols and values in Table 1:

$$\frac{\partial T(z,t)}{\partial t} = \frac{k}{\rho \cdot c_p} \cdot \frac{\partial^2 T(z,t)}{\partial z^2} \tag{2}$$

with the following boundary conditions:

$$-k \frac{\partial T}{\partial z}\bigg|_{z=0} = \dot{q}'' \qquad 0 \le t \le t^* \tag{3a}$$

$$T(0,0) = T_o \tag{3b}$$

$\dot{q}''$ [W/m^2] is the specific thermal power of the laser radiation determined by P / (Ø × s), being P and Ø the power and the spot diameter of laser beam, s the distance travelled by the laser in the unit of time at scanning speed V, T_o the initial temperature of the powder bed and t* the duration of radiation of incidence that can be estimated by

$$t^* = (Ø / V) \tag{4}$$

The temperature rise during the radiation incidence can be expressed analytically for a rectangular surface circumscribing the laser spot as

$$T(z,t) = T_o + 2\frac{\dot{q}''}{k} \cdot \left(\frac{\alpha t}{\pi}\right)^{1/2} \exp\left(-\frac{z^2}{4\alpha t}\right) - \frac{\dot{q}''}{k} \cdot z \cdot \text{erfc}\left[\frac{z}{2(\alpha t)^{1/2}}\right] \tag{5}$$

With polymer based powders, thermal sintering occurs already at a temperature lower than the melting point T_m: at the glass transition temperature T_g, agglomeration among grains is dominated by polymer chain rearrangement and cross-linking. The sintered material is included inside the envelope of T_g reached by the powder, where

agglomeration is activated. So equation (5) can be used to estimate the sintering depth z, and then the layer thickness obtainable in a single pass. As a particular case, from equation (5) we can estimate the history of the maximum temperature, which occurs on the surface (z=0)

$$T(0,t) - T_o = \frac{2q''}{k} \cdot \sqrt{\frac{\alpha t}{\pi}}$$ (6)

and should be kept below the polymer melting or degradation temperature.

HERE FIGURE 3

The point heat source model is the more commonly used in the literature, as in [7] [8], but it seems not suitable for high conductive polymers (k > 0.4 W/(m K)), because the thermal conduction in the lateral direction is not negligible with respect to the model preferential direction z. In addition, it is not suitable for high scanning speed because it is very sensitive to the selection of duration of incident radiation. To overcome the mentioned limitations, a different time dependent conduction model in which heat is generated instantaneously by a line heat source of intensity Q [J/m] can be proposed. This is a 1.5-dimensional model with a radial heat flow [21] along the cylindrical coordinate r with respect to the ideal axis as described in figure 3. The temperature increase around the line heat source can be expressed by

$$T(r,t) - T_o = \frac{Q}{4\pi kt} exp\left[-\frac{r^2}{4\alpha t}\right]$$ (7)

This model shows a direct connection between Q and the Energy Density, expressed in [J/mm^2], defined as

$$ED = \frac{P}{V \cdot \O}$$ (8)

a parameter commonly used in the literature [7] [8] [9] [12] [14] to express the SLS process parameters in energetic terms. Starting from the knowledge available in the literature it seems of relevant scientific interest to apply the aforementioned models in order to carry on evaluations on the energy aspects of the sintering process. The fact that many technological applications are characterized by a preheating phase of the powder bed introduces a further complexity in the definition of the boundary conditions of the physical problem.

3. Experimental methodology

It has been shown how a sintered structure is fabricated by a predefined sequence of layers. These layers are basically constituted of sintered lines flanked one on the other or partially superimposed. Thermal models have

been introduced to give an estimate of sintered line cross-sectional profile: the sintered depth determines the allowable layer thickness and is thus correlated with process resolution. The sintered width represents the transversal influence of laser radiation and limits the range of variation of the scan spacing between adjacent lines. It is then connected to the number of scanning lines to create a layer and consequently to process time.

In this study an experimental 3D SLS machine was used to produce sintered lines for varying levels of Energy Density (ED). This experimental apparatus, built for the laser sintering of pre-coated sand for shell moulding [10, 11], makes use of a CO_2 laser from SYNRAD with an almost Gaussian TEM (M^2=3). The laser emits a maximum average power of 50W in pulsed regime (50-200µs pulse duration) with a repetition rate ranging between 5-20kHz. The beam was deflected on the working surface by a mirror-equipped head with a maximum speed of 2.5m/s. A flat field lens (200mm focal distance) was used to maintain the beam focused on the whole sintering area to a minimum spot of 0.7mm diameter.

As stated before, DuraForm^{TM} Polyamide supplied by DTM Corporation (US) was used for the experiments since it is mostly used for this typical RP application. This powder contains for 98% of PA 12 by weight while the remaining part is titan bi-oxide. Table 1 lists the main properties of the adopted powder is used for model verification. Specific heat and thermal conductivity have been derived experimentally by the authors from a previous research and represent the main thermal characteristics needed to implement models mentioned in paragraph 2.

HERE TABLE 1

It can be noticed that the nylon powder has been selected because of its thermal properties (thermal conductivity and diffusivity) which are representative of the typical range of most thermoplastics used for rapid prototyping. Moreover the almost spherical grain shape and the average size distribution are quite uniform allowing an easier analysis of the agglomeration process.

The nylon powder was deposited on a special container by an automatic charging hopper which also levelled the polymer bed and thus guaranteed the flatness of the surface. The initial temperature of the polymer bed was kept at room temperature (20°C).

The range of Energy Density obtained from equation (7) and used in experiments, has also been preliminarily estimated by the aforementioned models and turned out to be comparable to those used in [8] and [9]. The Energy Density has been varied modulating the scanning speed and the laser power in the range respectively of 500-2500 mm/s and 50-12.5 W. The laser spot diameter Ø was kept constant at the minimum achievable size of 0.7mm for the experimental set-up. A combination of 16 different group of parameters have been tested, covering a wide range of energy density between 0.0071 and 0.2857 J/mm^2 as shown in table 2.

HERE TABLE 2

Table 2 showing the evaluation of the temperature obtained by means of equations (5) and (6), suggests that local melting on the surface could be expected at a value of energy density of about 0.08 J/mm^2.

Basic sintered structures fabricated by scanning 80mm long lines on the powder bed and showed in figure 4, were separated from the non-sintered polymer by emptying the powder container from bottom holes, which is shown in the second step of figure 4. Before starting this procedure, the sintered lines were glued to the supporting parts of the container by a single drop of acrylic resin, and thus avoided displacements or misalignments. As final step, non-sintered grains, which could affect the measuring process were removed by positioning the container on a vibrating device (frequency 1400Hz, amplitude 10µm) for 1 minute. As a consequence, powder grains linked to the structure by friction or by secondary hygrometric conditions could be easily eliminated maintaining the integrity of the structure.

The container was then placed under an optical microscope (resolution 5µm): with reference to figure 2, depth and width of the sintered lines were measured along the z axis and the y axis respectively.

HERE FIGURE 4

An example of sintered line is given in figure 5 where the top view shows the remarkable uncertainties in determining the contour, which defines the sintered width of a line. Because of the discontinuous nature of the sintered powder, average line width was measured in accordance with the following procedure:

- images of a fixed length (2.5mm) of the sintered lines (at 20X magnification) were taken under the structured light of the microscope allowing a good contrast between nylon powder and the background;
- images were then binarized using Matlab® Image-Processing toolbox. The same software was also used to plot the envelopes of the boundary lines and to determine the surface area included between them by pixel-counting.
- Finally the area was then divided by the characteristic length to derive the average value of the width.

This procedure was repeated for three different portions of the sintered line within the measurement zones depicted in figure 5.Values obtained by this multiple measuring method have been then averaged.

The same procedure was followed to determine the average depth of the sintered lines, placing the container in a position which allows measurements on planes parallel to x-z.

The average line depth is directly related to the thickness of a layer obtained from a predetermined Eenergy Density input. On the other hand, the average width represents the limit value for the scan spacing parameter, to be used for a certain energy density in order to guarantee a correct overlap between adjacent sintered lines.

HERE FIGURE 5

4. Experimental results

In this paragraph the results of the experimental investigation carried out are exposed and briefly discussed. Each testing condition in figures 6 to 9 is represented as the average value obtained in three different measurements, as explained in previous section. Figure 6 contains the dimension of the lines obtained as a function of energy density. From Figure 6 it can be noticed that width and depth of line scanned increase with the Energy Density.

For low values of ED (0.02-0.03 J/mm^2), depth is about half of width corresponding to a cylindrical distribution of isothermal surfaces, as can be predicted by the instantaneous line heat source model given in equation (7). For the powder tested (DuraForm^{TM} Polyamide), width is predominant over depth up to the Energy Density of about 0.10 J/mm^2 and reaches about 0.5 mm. This, in fact, acts as a limit value that largely depends on the laser spot diameter. This phenomenon can be attributed to its low conductivity and diffusivity which keep heat localised in the irradiated area. This can also can be extended to all those thermoplastic powders with similar thermal properties (e.g. PS, PMMA, PC, PE).

Depth increases more than width and almost linearly until it reaches an asymptotic limit. This is because of the preferential heat diffusion along z-axis, as the point heat source model describes. The linear trends of figure 6 are upper limited by thermal constraints, suggested by the exponential nature of the point heat source model in equation (5). Figure 7 analyzes the difference between the depth of the layer agglomerated and the thickness of the heat affected zone (HAZ). Heat affected zone was defined as the distance between the more distanced sintered grains along z and was measured following the same procedure described for the line depth. From the figure, it can be observed that for low values of energy density the HAZ zone and the agglomerated dimension are quite similar. For values higher than 0.10 J/mm^2 the difference between the two dimensions is remarkable. This means that a substantial amount of melting or even a vaporization process occurs on the surface grains due to the additional energy input. This is the reason why the effective depth of the sintered lines reaches a limiting value, while HAZ increases linearly with ED. These phenomena, in turn, reflect the balance between further conduction along z-axis and vaporization on the surface.

In figure 8, the Volumetric Productivity (VP), obtained as the product of scanning speed by width and depth in figure 6, is plotted as a function of the Energy Density.

Finally figure 9 provides the Volumetric Energy Intensity (VEI), which is obtained as a ratio of the laser power to Volumetric Productivity in figure 8. This term is also used to expresses the agglomeration efficiency of laser power.

Similarly to [18] the Volumetric Energy Intensity can be considered as an indicator of the specific energy consumption of the process. In optimal conditions the Volumetric Productivity should be maximised and the Volumetric Energy Intensity should be minimised. From data 250 mm^3/s, was found to be the highest Volumetric Productivity for DuraForm^{TM} Polyamide. In the range of 0.06-0.08 J/mm^2 both productivity and energy intensity are found optimal for the polymer tested and close to those values pointed out by other researchers [9]. The process resolution is also good in the aforementioned range.

In the optimal conditions, productivity and agglomeration efficiency can be increased up to 100% within the specified range of the SLS parameters. The Volumetric Energy Intensity of the examined processes is one order of magnitude lower than conventional processes discussed in [18].

Figures 8 and 9 show that for the polymer tested as well as for those with similar thermal characteristics, different energy consumptions are required to obtain different process rates within the range of the tested Energy Density. It is important to underline that these considerations have been achieved without preheating. In some conditions removing preheating represents an additional energy saving option, when allowed by technological constraints (distortion, mechanical resistance, etc.) reviewed in [5] but not considered in the present work.

Optimal theoretical sintering conditions (an energy consume of about 0.2 J/mm^3 compared to a productivity of about 230mm^3/s) can be derived from both the charts and have been used to numerically characterize the process of laser sintering of polymer-based powders in accordance to the statements reported by Gutowski et al. in [20]. In their work authors give specific electricity requirements for various manufacturing processes as a function of the rate of material processed. Analyzing the data obtained in the experimental analysis and comparing them with those provided in Fig. 5 of [20] it is possible to observe that, from an energetic perspective, SLS of the tested powder is located at a quite low level with respect to other conventional manufacturing processes.

The analysis of the experimental results analyzed in the previous section show that there is a range in which it is convenient to operate. As a matter of fact, if the energy density is too high the productivity of the process is reduced. This is because of a superficial melting of the material as well evidenced by the analysis of the line scanned. This could also be obtained by means of the thermal model given in equations (5) and (6). From these models it is clearly evident the surface temperature reaches its melting point if a Energy Density input is approximately 0.08 J/mm^2. For higher values of ED, the productivity decreases as a part of energy introduced into the layer serves for the local melting of the material and has no contribution to the sintering process.

Moreover the analyses of the experimental results testify that these simple models are able to describe sintering phenomena and predict the results.

HERE FIGURES 6-9

5. Conclusions

The energetic aspects of SLS process have been investigated paying particular attention to the correlation between the technological results and the energy input in the process characterized by the Energy Density parameter. The results obtained show that the energetic intensity of the process is quite low because it ranges between 0.2 and 0.6 J/mm^3 operating with energy density in the range between 0.015 and 0.3 J/mm^2. In particular a range of parameters for a SLS process of a common thermoplastic powder (DuraForm^{TM} Polyamide) has been explored and an approach for a multicriteria optimisation based on combination of resolution, productivity and energy has been proposed. The effects on sintering of the process parameters can be synthesised by the Energy Density which is directly correlated to the instantaneous line heat source model. Laser power, scanning speed and laser spot diameter can be varied within the examined order of magnitude. Measurements show that the best results can be obtained operating with energy density in the range between 0.02 and 0.07 J/mm^2; in this range all the laser energy is useful for the process.

Models alone are not profitably applicable for quantitative evaluations without experimental support, but they allow to understand phenomena and to reduce the amount of experimental work during the set-up process of a commercial machine. By the two simple, analytical, one-dimensional thermal models the temperature distribution and the line scan size and spacing can be *preliminarily* estimated. Concerning the accordance between experimental results and the theoretical modelling of the process, results demonstrate the dominating effect of the polymer thermal properties, particularly conductivity and diffusivity. It seems then reasonable to

extend similar considerations also to other polymer powders whose thermal conductivity and diffusivity are not far from the ones of the DuraForm^{TM} Polyamide.

Moreover it can be evidenced that the classical instantaneous point heat source model can be satisfactory for describing the SLS process for energy density higher than 0.03 J/mm^2, while the instantaneous line heat source model that has been proposed and compared with the classical point heat source model can be better for describing the behaviour at lower value of energy intensity.

As concluding remark, the SLS process of single lines, which represent the basic structures for the fabrication and consolidation of a layer, has been analyzed from an energetic point of view varying the Energy Density. The mechanical resistance of these basic structures has been only indirectly checked during the measuring methodology when sintered lines undergo to micro-vibration in order to be extracted by the un-cured powder. On the other hand the resultant mechanical characterization (residual stresses, distortion etc.) of a complete 3D structure, realized by the suggested process parameters, is not discussed in the present paper. It is then important to underline that data provided in this paper cannot be directly compared to other Rapid Prototyping techniques or other conventional manufacturing processes from the perspective of the quality (mechanical properties, surface roughness, wear resistance, etc.) of a final product.

Since every production process should undergo to the twofold objective of maintaining the best product characteristics with the lowest energy consumption, it is therefore desirable that the analysis on Energy Density efficiency for the sintering process, provided in this paper, should be combined to a further technological and mechanical study on products obtainable in the selected range of ED. Those last issues cannot be considered from a general perspective like in the one shown in the present paper, but require a more detailed definition of the geometrical shape of structure to be tested and represent an important key-factor for a further analysis.

REFERENCES

[1] US Environmental Protection Agency (EPA), 2009, Toxics Release Inventory (TRI) 2007, Report available at http://www.epa.gov/tri/tridata/tri07/index.htm .

[2] J. F. Schifo, J.T. Radia, 2004, Theoretical/Best Practice Energy Use in Metal casting Operations, Report available at http://www1.eere.energy.gov/industry/metalcasting/pdfs/doebestpractice_052804.pdf.

[3] Gutowski T.G., Branham M., Dahmus J., Jones A. J., Thiriez A., Sekulic D.P., 2009, Thermodynamic analysis of resources used in manufacturing processes, Environmental Science and Technology, 43: 1584–1590.

[4] Levy G.N., Schindel R., Kruth J.P., 2003, Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives, Annals of the CIRP, 52/2:589-609.

[5] Kruth J.P., Levy G., Klocke F., Childs T.H.C., 2007, Consolidation phenomena in laser and powder-bed based layered manufacturing, Annals of the CIRO, 56/2: 730-759.

[6] Kandis M., Bergman T.L., 2000, A simulation-based correlation of the density and thermal conductivity of objects produced by laser sintering of polymer powders, J.Manuf. Sci. and Eng., 122/3: 439-444.

[7] Childs T.H.C., Tontowi A.E., 2001, Selective laser sintering of a crystalline and a glass-filled crystalline polymer: experiments and simulations, Proc. IMechE, Part B: J. Engineering Manufacture, 215:1481-1495.

[8] Berzins M., Childs T.H.C., Ryder, G.R., 1996, The selective laser sintering of polycarbonate, Annals of the CIRP, 45/1:187–190.

[9] Childs T.H.C., Berzins M., Ryder G.R., Tontowi A.E., 1999, Selective laser sintering of an amorphous polymer: simulations and experiments. Proc. IMechE, Part B: J. Engineering Manufacture, 213:333-349.

[10] Dini G., Franco A., Lanzetta M., Santochi M., Tantussi G., 2001, An Analytical Model of Selective Laser Sintering (SLS) of Pre-Coated Sands for Shell-Moulding, Proc. 5th AITeM Conf., Bari, Italy, 18-20/09/2001, 1:113-128.

[11] Dini G., Franco A., Lanzetta M., Santochi M., Tantussi G., 1999, An Approach Study for Selective Laser Sintering (SLS) of pre-coated sands for Shell-Moulding, Proc. 5th AMST Conf., Udine, Italy, 3-4/06/1999:545-556.

[12] Hon K.K.B., Gill T.J., 2003, Selective Laser Sintering of SiC/Polyamide Composites, Annals of the CIRP, 52/1:173-176.

[13] Partee B., Hollister S.J., Das S., 2006, Selective Laser Sintering Process Optimization for Layered Manufacturing of CAPA® 6501 Polycaprolactone Bone Tissue Engineering Scaffolds, Trans. ASME, J. Manufacturing Science and Engineering, 128:531-540.

[14] Schmidt M., Pohle D., Rechtenwald T., 2007, Selective Laser Sintering of PEEK, Annals of the CIRP, 56/1:205-208.

[15] Shi Y., Chen J., Wang, Y., Li, Z., Huang, S., 2007, Study of the selective laser sintering of polycarbonate and postprocess for parts reinforcement, Proc. IMechE, Part L: J. Materials: Design and Applications, 221:37-42.

[16] Dini G. Franco A., Lanzetta M., Santochi M., Tantussi G., 2001, Thermo-Physical Characterization of Pre-Coated Sands for Shell-Molding, Proc. 5th AITeM Conf., Bari, Italy, 18-20/09/2001, 1:159-170.

[17] Ruffo M., Hague R.J.M., 2007, Cost estimation for rapid manufacturing - simultaneous production of mixed components using laser sintering, Proc. IMechE, Part B: J. Engineering Manufacture, 221(B11):1585-1591.

[18] Yanchun L., Zhiming J., Leu M.C., Caudill, R., 1999, Environmental performance analysis of solid freedom fabrication processes, Proc. ISEE, IEEE International Symposium on Electronics and the Environment, Danvers, MA, USA, 11-13/05/1999:1-6.

[19] Morrow W.R., Qi H., Kim I., Mazumder J., Skerlos, S.J., 2007, Environmental aspects of laser-based and conventional tool and die manufacturing, J. Cleaner Production, 15:932-943.

[20] Gutowski T.G., Dahmus J., Thiriez A., 2006, Electrical Energy Requirements for Manufacturing Processes, 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium.

[21] Bejan A., 1993, Heat Transfer, J. Wiley & Sons.

Tables and captions

Symbol	Definition	Unit	Value
ρ	density (non pressed)	kg/m^3	840
-	apparent density	%	75
-	average grain size	mm	0.05
c_p	specific heat	kJ/(kg K)	2.5
α	thermal diffusivity (k / ρ c_p)	m^2/s	6.1×10^{-8}
k	thermal conductivity	W/(m K)	0.13
T_g	glass transition temperature	K	333-343
T_m	melting temperature	K	438-458

Table 1. Properties of DTM DuraForm^{TM} Polyamide.

P [W]	V_{scan} [mm/s]	En_{spec} [J/m]	Energy Density [J/mm^2]	$T_{max} - T_{amb}$ [°C]
12.5	2500	5	0.0071	15.4
12.5	1250	10	0.0143	30.8
12.5	833	15	0.0214	46.3
50	2500	20	0.0286	61.7
50	2000	25	0.0357	77.1
50	1500	30	0.0476	100.2
50	1250	40	0.0571	120.2
50	1000	50	0.0714	150.3
50	833	60	0.0857	180.4 (melting)
50	714	70	0.1000	melting
50	625	80	0.1143	melting
50	555	90	0.1287	melting
50	500	100	0.1429	melting
50	333	150	0.2145	melting
50	250	200	0.2857	melting

Table 2. Experimental tests and theoretical evaluation of maximum surface temperature increase.

Figures and captions
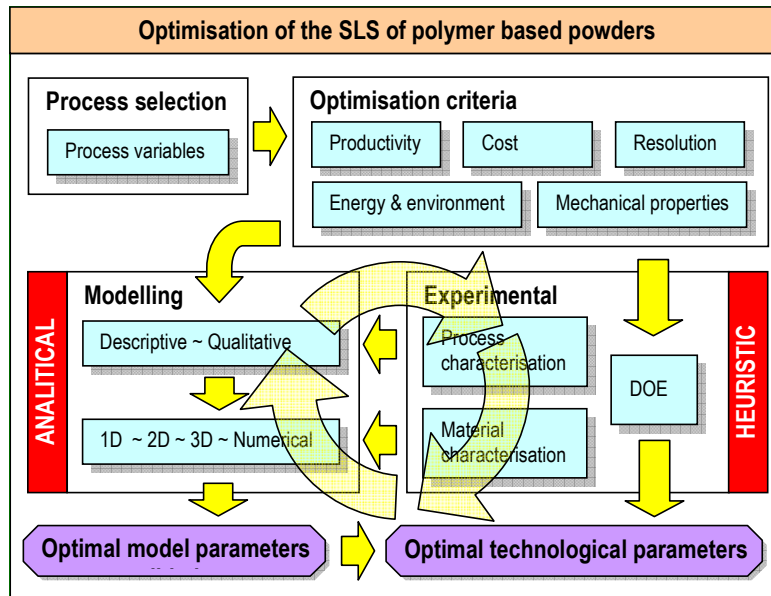
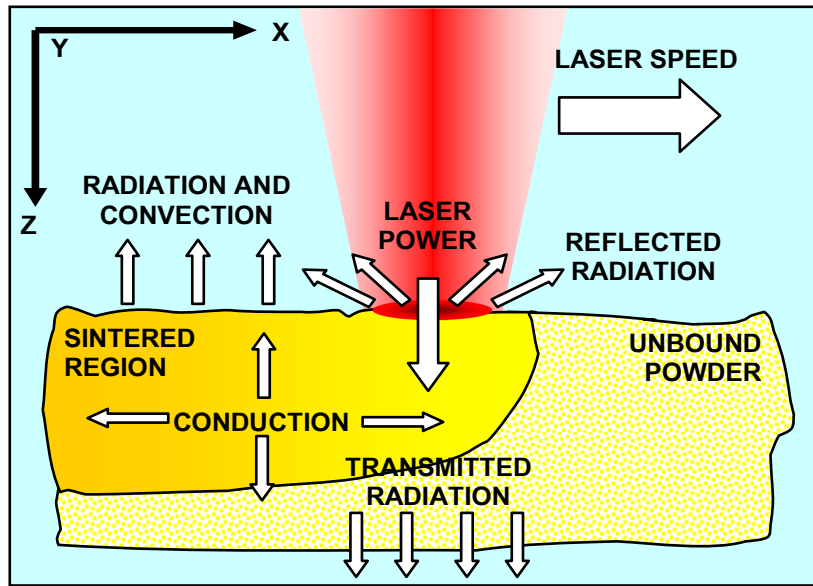Figure 1. The concept of multi-objective optimisation method

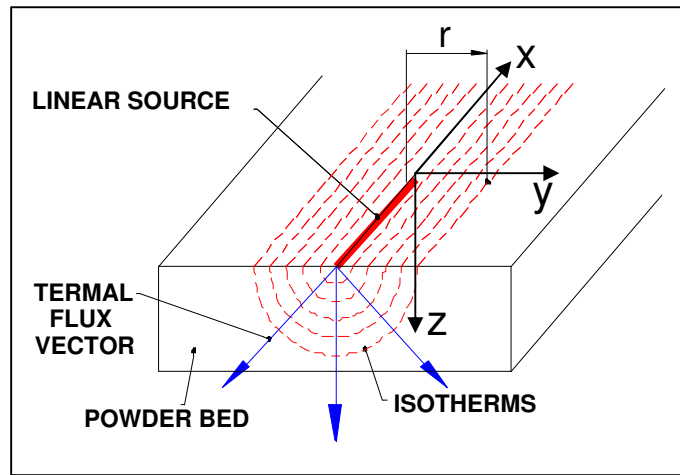Figure 2. The main energy terms in SLS.

Figure 3. Instantaneous line source of heat generating semicylindrical isotherms.
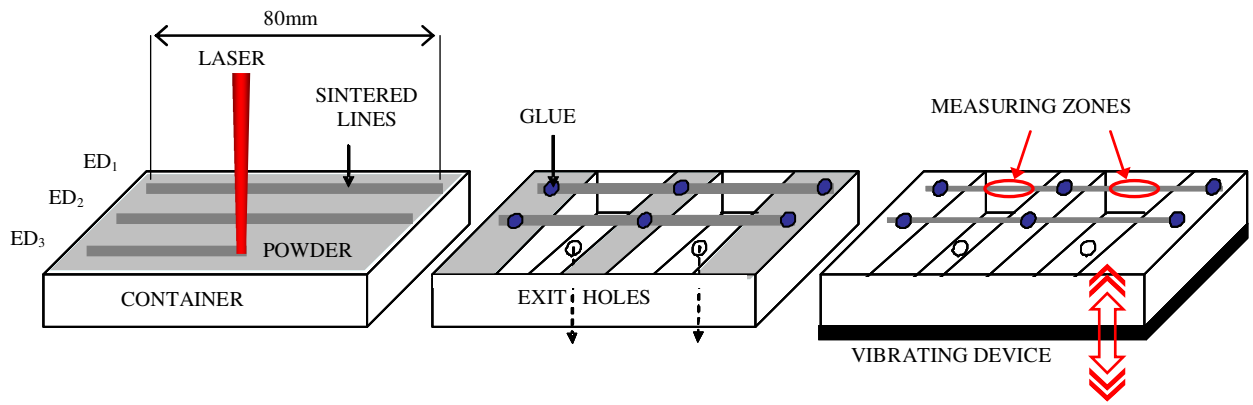
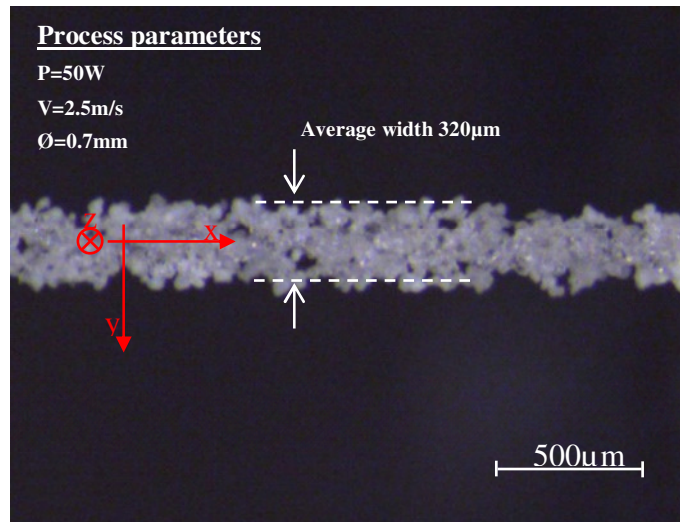Figure 4. Draft of the extraction procedure of the sintered lines.

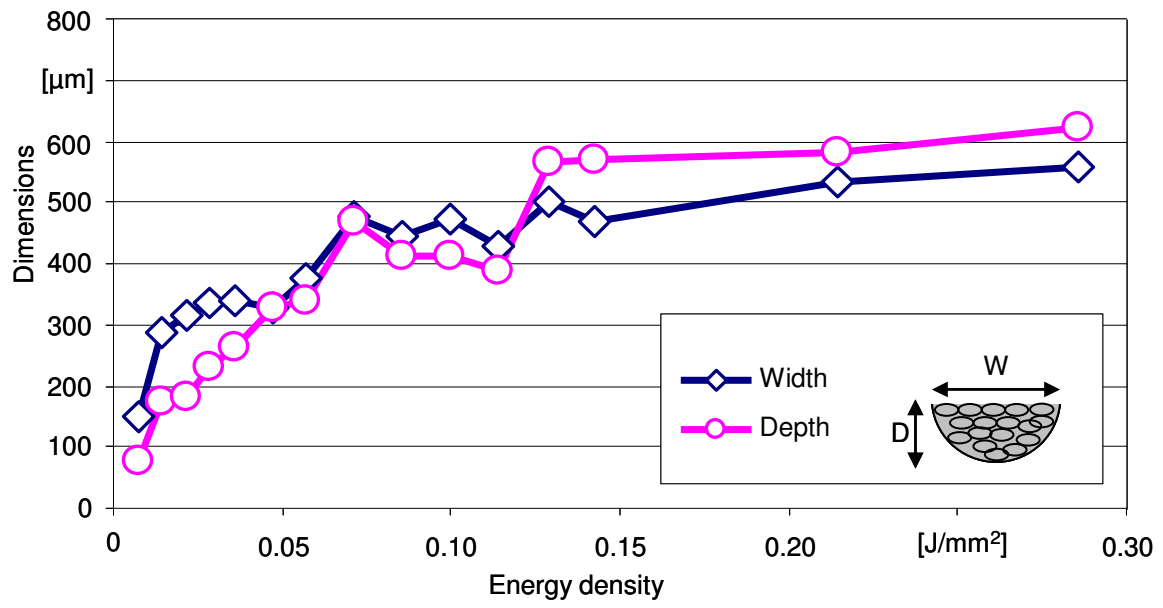Figure 5. Top view of a sintered line and measure of the averaged width.

Figure 6. Main dimensions of the profile of sintered lines (width and depth) as a function of the Energy Density adopted.
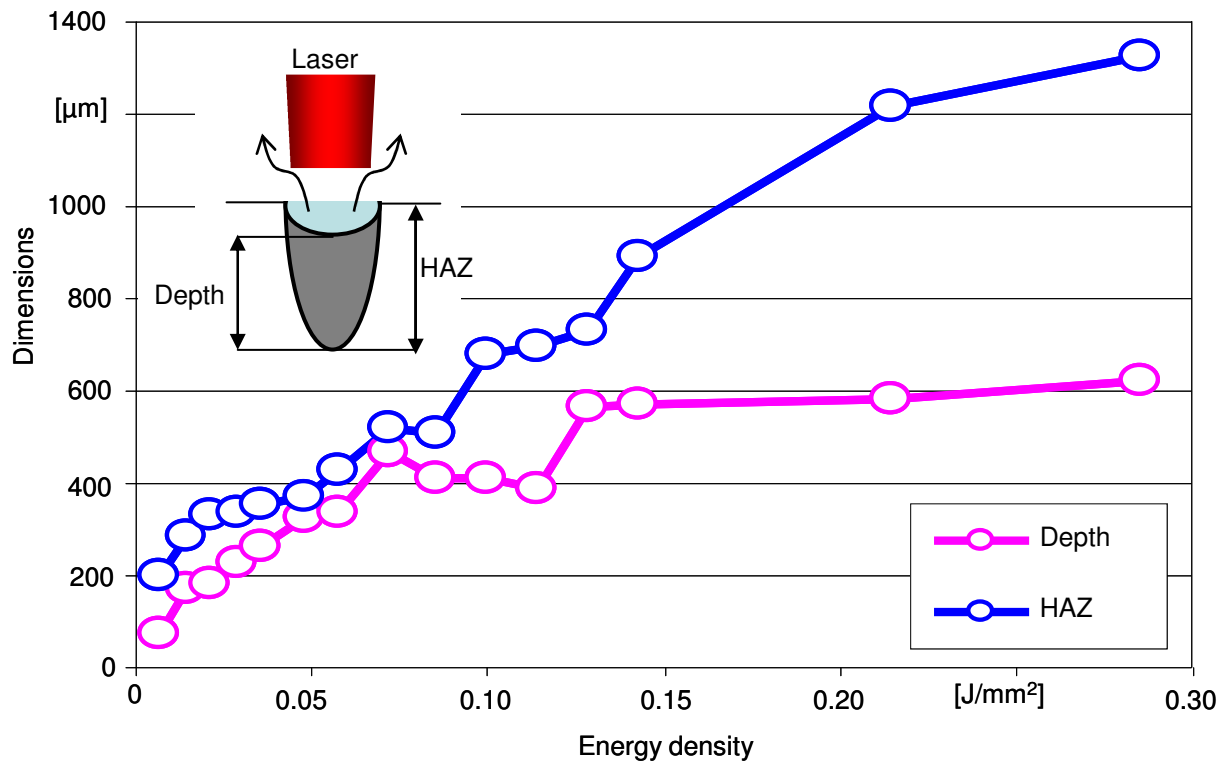
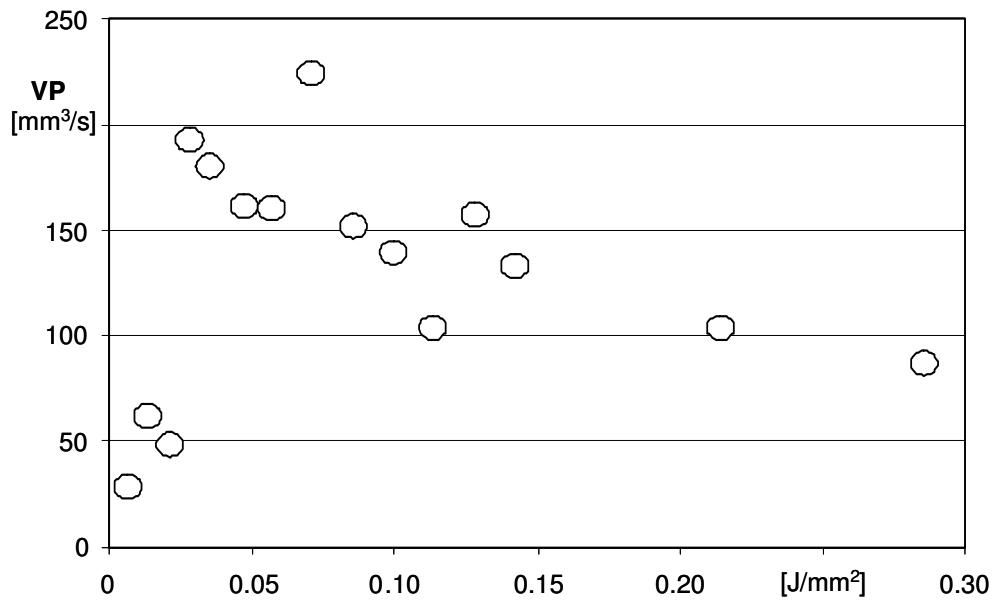Figure 7. Difference between penetration of the thermal front and heat affected zone

Figure 8. Volumetric Productivity versus Energy Density: a productivity indicator as a function of the process parameters.
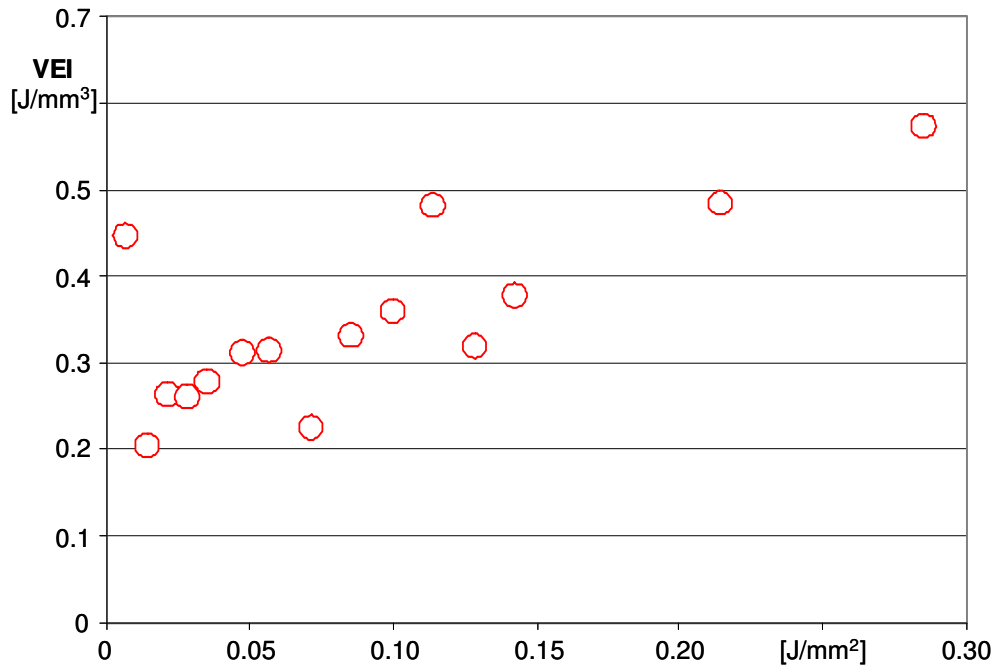
Figure 9. Volumetric Energy Intensity versus Energy Density: an energy performance indicator as a function of the process parameters.