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Experimental analysis of selective laser sintering of polyamide powders: an energy perspective

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This paper presents an analysis of Selective Laser Sintering (SLS) from an energy standpoint. 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 Volumetric Energy Intensity (VEI) of the process in optimal condition could be of the order of 0.2 J for each mm^3 of material agglomerated.

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 (USEPA, 2007; Schifo and Radia, 2004). Energy consumption is a component of environmental impact and it is a critical component in any overall sustainability strategy (Gutowski et al., 2009). A relevant paper about the energy requirements of manufacturing processes could be found in Gutowski et al. (2006).

In order to tackle the issues for achieving sustainable production and improve process performance, in alternative machining technologies, the main objectives under consideration are as follows

- To reduce machining processes energy consumption.
- To minimize waste (generate less waste and increase waste reusage or recycling).
- To use resources efficiently.

Hence reducing energy usage is an essential consideration in sustainable manufacturing. For example, in a recent study, Pusavec et al. (2010a,b) suggested a number of ways to improve sustainability in manufacturing. Reducing the energy consumed in manufacturing processes was identified as one of the strategies.

Even if the energy consumed for non-cutting operations dominates the total energy consumption in machining (Rajemi et al., 2010).

Optimisation of machining operations has been undertaken for a considerable number of years based on technological and economic considerations. The current and urgent need to reduce energy consumption requires a knowledge base for selection of minimum environmental processing conditions. The optimum condition for minimum costs does not necessarily satisfy the minimum energy criterion.

For this purpose laser assisted manufacturing processes like Rapid Prototyping techniques, when compared with traditional manufacturing processes, have the potential to reduce cost, increase surface resistance to wear and fatigue, extend part/tool life, and expand the range of manufacturable materials. They also 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.

However, to date, very little research has been conducted to evaluate and compare the environmental performance (e.g.

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Nomenclature

abs	absorption coefficient
c_p	specific heat, J/kg K
En_{spec}	specific energy (= P/V), J/m
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_{amb}	environmental temperature, K
T_g	glass transition temperature, K
T_{max}	maximum estimated temperature of powder bed, K
T_0	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 (= $k/\rho c_p$), m^2/s
Ø	spot diameter of laser beam, μm
ρ	density, kg/m^3

greenhouse gas emissions or carbon footprint) of laser assisted manufacturing processes relative to the traditional manufacturing methods. It is critical for engineers to design and develop novel processing techniques that are more environmentally friendly without sacrificing functionality, performance, and economic viability (Zhao et al., 2010).

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 (Levy et al., 2003). 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 layer 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. (2007).

- 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 and Bergman (2000), 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.

Polymers have been widely used in the selective laser sintering (SLS) process. It is well-known that one of the advantages of the SLS process is to make very complex parts without need of molds as compared with traditional manufacturing methods. Consequently, accuracy is very important for SLS parts, and part accuracy must be preferentially considered in addition to the energy related data when processing parameters are selected. Very few studies are present in the literature considering this connection.

The effects of laser energy density on the relative density, mechanical properties like flexural strength and microscopic morphology, and dimensional accuracy of the SLS parts were studied in Yan et al. (2010). The authors found that SLS specimens made with a quite reduced value of energy density (of the order of 0.08 J/mm^2) have relatively higher dimensional accuracy. Therefore, the authors suggested energy density of 0.08 J/mm^2 to make green SLS parts.

In Zarringhalam et al. (2009) SLS specimens were produced under different build parameters, in order to vary the amount of energy input, and DSC traces produced for each. DSC results were also compared with optical microscopy images to confirm the findings.

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.