Densification Kinetics of Steel Powders during Direct Laser Sintering

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Abstract

It is known that powder characteristics including particle size and distribution, particle shape, and chemical composition are important parameters which influence direct laser sintering of metal powders. In this paper, we introduce a first order kinetics model for densification of steel powders during laser sintering. A densification coefficient (K) is defined which express the potential of different powders to be laser-sintered to a high density dependent on their particle characteristics.

Keywords: rapid prototyping; direct laser sintering: sintering model; densification; steel powders

1. Introduction

Laser sintering is one of the leading commercial processes for rapid fabrication of functional prototypes and tools. The process creates solid three-dimensional objects by bonding powdered materials using laser energy. Different material systems such as engineering plastics, thermoplastic elastomers, metals, and ceramics are in use [1]. Although the process can be applied to a broad range of powders, the scientific aspects of the production route such as sintering rate have not been well understood. This method of fabrication is accompanied by multiple modes of heat, mass and momentum transfer, and chemical reactions that make the process very complex. Recently, many works, for example [2, 3], have been performed to develop computer models for the laser sintering. Nevertheless, to allow the evaluation of density as a function of time and temperature and thus on the process variables, it is important to develop a sintering model. A sintering model allows one to perform a parametric analysis to study how variations in one parameter affect the sintered density or sintering depth within a powder bed. In this paper, a *first order* sintering kinetic rate is introduced for direct laser sintering of steel powders based on empirical results. Although steel powders were used for experiments, the results are generic and can be applied for other metal powders.

2. Experimental and Results

Various iron powders with different particle size and distribution, 316L stainless steel, M2 high-speed steel, graphite, copper, and ferro-phosphorous powders were used in this study. The detail of material characteristics has been described in [4]. Different powder blends with various chemical compositions were prepared by powder blending in a tumbling mixer for 30 min. The powder blends were then sintered layer by layer to rectangular test specimens using EOS M250X$^{\text{tend}}$ machine. The detail of laser sintering operation has been given in [5]. Many samples were fabricated and the density of the specimens was determined by the water displacement (Archimedes) and volumetric methods.

Fig. 1 shows the fractional density of laser sintered powders as a function of the ratio of laser power (P) to scan rate (v). To a first approximation, it seems that the density is linearly proportion to P/v in semi-log scale. If the effect of layer thickness (w) and the hatch (h) is also considered, the energy delivery to the system per unit volume would be described by [6]:

$$\psi = \frac{P}{h\,v\,w} \tag{1}$$

The delivered energy is related to the sintering temperature (T_s) by:

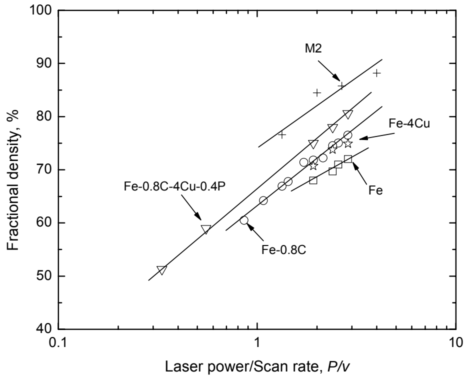


Fig. 1. Fractional density of laser-sintered steel powders as a function of the ratio of laser power to scan rate.

$$T_s = T_0 + \frac{1}{C}\left[(\frac{\pi \eta}{4\rho})\psi - \Delta H \right] \qquad (2)$$

where C is the heat capacity, η is the laser coupling efficiency, ρ is the density, and is the ΔH latent heat of melting. Therefore, as ψ increases, a higher density should be attained. It means that the sintering rate is directly related to ψ. According to the *first order* kinetics law, the rate changes in the void fraction of powder bed in the laser sintering process can be described as:

$$\frac{\partial \varepsilon}{\partial t} = -k^{'} \varepsilon \qquad (3)$$

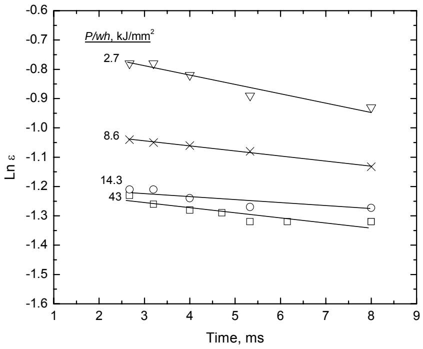


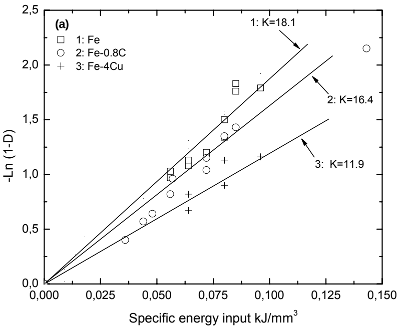
Fig. 2. Void fraction of the laser-sintered iron part as a function of the exposure period of the laser irradiation.

Fig. 2 illustrates the variation of porosity (ε) with the exposure period of the laser radiation as an example for iron powder with particle size< 50 µm. The plot clearly shows that the first order kinetic model is valid. As it has been shown elsewhere [4], the rate constant of the equation (k') is linearly related to ψ. Therefore, if the amount of densification (D) is defined as Equation (4), the sintering equation would be in the form of Equation (5).

$$D = \frac{\varepsilon - \varepsilon_b}{\varepsilon_s - \varepsilon_b} \qquad (4)$$

$$Ln\,(1 - D) = -K\,\psi \qquad (5)$$

where ε_b is the porosity of the powder bed, ε_s is the maximum attainable density by laser sintering of a particular material, and K is the densification coefficient. Fig. 3 shows plots of "-Ln(1-D) versus ψ" for the examined materials according to the experimental data. The straight lines yield the densification coefficient, K, which in turn, higher values means less densification during laser sintering process. The diagrams show the validity of the sintering model. Based on K-values, one can evaluate and compare the sinterability of different powder material systems. For instance, the positive influence of the addition of C and Cu on the densification of Fe powder is deducible from Fig. 3a. While 316L stainless steel powder shows good sinterability (Fig. 3b), M2 high-speed steel has a high K-value (28.3), meaning that this powder is not suitable for processing because of low attainable density.



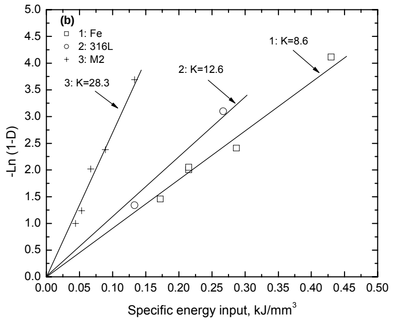


Fig. 3. The densification (D) of metal powders as a function of the delivered laser energy (ψ). The particle size of the powders are <100 µm (a) and <45 µm (b).

3. Summary

In the present work, a simple sintering kinetics model was suggested for direct laser sintering of metal powders. It was shown that the densification of a powder bed during laser sintering is directly proportion to the delivered laser energy. A densification coefficient (K) was introduced, by which, one can compare the sinterability of different powders. Based on the empirical sintering data, the value of K was determined for various steel powders subjected to laser sintering. It was shown that the addition of C, Cu, and P improves the sinterability of iron powder. The processability of 316L stainless steel was found reasonable in contrast to what is seen for M2 high-speed steel.

4. References

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