



Selective laser melting of fused silica: Interdependent heat transfer and powder consolidation



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ABSTRACT

Fused silica is promising for layer-by-layer additive manufacturing by selective laser melting of its powder. This material is resistant to thermal shocks associated with the laser treatment. Experiments show feasibility of such a process. However, the window of acceptable process parameters seems to be very narrow. The reason is a very high viscosity of fused silica, even at elevated temperatures, because powder consolidation is controlled by viscous flow. Experimental results are analyzed with the developed mathematical model considering powder consolidation by merging softened particles. To calculate heat transfer in the consolidating powder bed, a theoretical approach to the effective thermal conductivity is proposed. The numerical modeling can predict the experimentally observed structure of the laser track. To control the quality of the obtained material, the most important process parameters are the laser power, the thickness of the powder layer, and the preheating temperature. The laser power should be sufficient to heat the surface up to the boiling point. To attain complete consolidation in the critical zone situated at the bottom of the powder layer, the thickness of the layer can be reduced. Numerical modeling indicates that another effective way to increase the temperature and the consolidation degree in the critical zone is to apply preheating.

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1. Introduction

Recent advance in additive manufacturing is explained by a demand from various high technology domains as prosthetics, tool manufacturing, and aeronautics. Rapid and precise shaping in additive processes is attained at layer-by-layer growth of a manufactured part. The selective laser melting (SLM) is the additive manufacturing process using powder as initial material. The growth of the part is provided by fusing a powder layer by a scanning laser beam. This is why the physics of interaction of a laser beam with a powder bed was studied both experimentally [1–4] and theoretically [1,3,5–7]. The principal physical processes of this interaction are transfer and absorption of laser radiation, heat transfer, and powder consolidation. The experiments give detailed information about the formed structures. However, the dynamics of the process is insufficiently studied. This is why the consolidation mechanism of metallic powders is not completely understood.

The cited theoretical works are based on various consolidation models, which are not fully validated experimentally.

Up to now, scientific discussions continue in the three domains of transfer and absorption of laser radiation, heat transfer, and powder consolidation. Thus, Refs. [8,9] concerned radiative properties of packed beds, Ref. [10] was dedicated to radiative heat transfer, Refs. [11–14] dealt with conductive heat transfer, and Ref. [15] investigated superposition of radiative and conductive heat transfer in packed beds. Melting and coalescence of particles at heating of packed beds was studied in Refs. [7,16]. However, the mutual influence of the three physical processes at SLM is poorly studied.

Solid material formed by SLM is subjected to strong thermal shocks during the process of manufacturing. This is why SLM is suitable for metals and polymers resistant to thermal shocks. The attempts to apply this technology to ceramic materials like alumina [17] and zirconia [18] failed because these materials cracked. The cracking is explained by high thermal expansion and a high elastic modulus resulted in thermal stresses greater than the mechanical strength of the material. The extremely low thermal expansion coefficient of fused silica makes it promising for using at SLM. Indeed, thermomechanical modeling of SLM process [19] revealed that the maximum tensile stress is not greater than the tensile strength of fused silica. The possibility of crack-free SLM

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of fused silica was experimentally confirmed [4]. The advantages of fused silica over many metals and polymers are high corrosion resistance and important high-temperature strength. Therefore, development of SLM technology for fused silica would be a considerable progress.

The principal difficulty at SLM of fused silica is slow powder consolidation because of a very high viscosity in liquid state. Complete consolidation is possible but can be attained in a very narrow domain of process parameters [4]. A precise process control is necessary to obtain uniform low-porosity parts of fused silica by SLM. The objective of this work is to develop and experimentally validate a mathematical model for SLM of fused silica. Such a model is expected to be useful in process optimization and control like existing models for metals [1,5,20]. The difference is that the time of coalescence of molten particles of metal powder is negligible [5] while this time for softened particles of fused silica is comparable to the overall time of laser/powder interaction at SLM. The particles of powder bed coalesce by forming necks between them [21]. The necks grow reducing the surface energy of the powder bed [21]. Conductive heat transfer in the powder bed is controlled by the necks [22]. This is why heat transfer depends on the kinetics of powder consolidation. On the other hand, neck growth is controlled by viscous flow of softened fused silica. The viscosity of fused silica strongly depends on the temperature. Therefore, the kinetics of powder consolidation depends on heat transfer.

2. Model

Solid parts are built at SLM layer-by-layer. The conditions of laser/matter interaction are similar at each layer. Therefore, the model considers laser treatment of one layer. The laser beam scans the surface of the target along straight lines with constant speed u as shown in Fig. 1. Before scanning the target consists of a powder layer of thickness L deposited on the top of previously consolidated layers. The consolidated layers constitute a solid substrate of the same material. The heat affected zone at SLM attains few layer thickness [5] while the total number of layers can be several hundreds. Therefore, the substrate is supposed to be thermally thick. Thermal conditions for laser scanning can be different for the very beginning of part growth. Note that a physical solid substrate is used to start growth. The material of the substrate can be the same as that of the powder. In this case, the thermal conditions for laser treatment of the first and the subsequent layers are equal.

Powder with the maximum particle diameter $D = 20 \mu\text{m}$ was used in experiments [4]. The thickness of the powder layer L varied from 100 to 200 μm [4]. In such conditions, a detailed description of the heterogeneous two-phase solid/gas structure of the powder layer is excessive. The approach of effective homogeneous medium is reasonable. The small parameter is D/L . Both in homogeneous

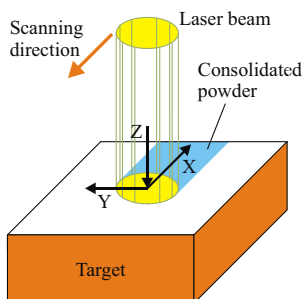


Fig. 1. Laser beam, target, and the frame.

(the substrate) and in heterogeneous (the powder layer) domains of the target, conductive heat transfer is described by the same equation written in the frame moving with the laser beam as shown in Fig. 1:

$$\frac{\partial H}{\partial t} = \nabla \cdot (\lambda \nabla T) + u \frac{\partial H}{\partial x}, \quad (1)$$

where H is the (effective) volumetric enthalpy, λ the (effective) thermal conductivity, ∇ the operator nabla, t the time, and T the temperature. The last term in the right hand side of Eq. (1) is due to movement of the frame relative the medium.

Molar enthalpy of fused silica $h(T)$ obtained from experimental data [23] is shown as curve 1 in Fig. 2. Vertical dotted lines indicate the characteristic temperatures of fused silica listed in Table 1. Approximating line 2 is accepted for calculations in this work, corresponds to the specific heat of 73 J/(mol K). With the molar mass of SiO_2 and the density of fused silica of 2.2 g/cm³, the molar specific heat is recalculated to the volumetric one $C_p = 2.68 \text{ MJ}/(\text{m}^3 \text{ K})$. Finally, the volumetric enthalpy of the target is

$$H = (1 - \varepsilon)C_p T, \quad (2)$$

where ε is the porosity equal to the volume fraction of the gas phase. The contribution of the gas phase into enthalpy is neglected. It is known that addition of an arbitrary constant to the function of enthalpy versus temperature has no impact. The constant for the molar enthalpy shown in Fig. 2 is chosen so that the curve passes point (300, 0) while the constant for volumetric enthalpy H given by Eq. (2) is chosen so that the function passes point (0, 0). The independent choice of the constants is possible because the molar enthalpy is used to obtain the specific heat, which is not influenced by the constants.

2.1. Powder consolidation

The softened particles of fused silica behave like the droplets of viscous liquid. They tend to coalesce as shown in Fig. 3. The extent of coalescence is characterised by neck diameter a . The kinetics of neck growth between two spherical particles of diameter D is estimated as [21]

$$\frac{d\xi^2}{dt} = \frac{3\delta}{\eta D}, \quad (3)$$

where $\xi = a/D$ is the relative neck diameter, δ the surface tension coefficient, and η the dynamic viscosity. The surface tension coefficient of fused silica does not considerably vary with temperature and equals about $\delta = 0.4 \text{ N/m}$ [26]. On the contrary, the viscosity

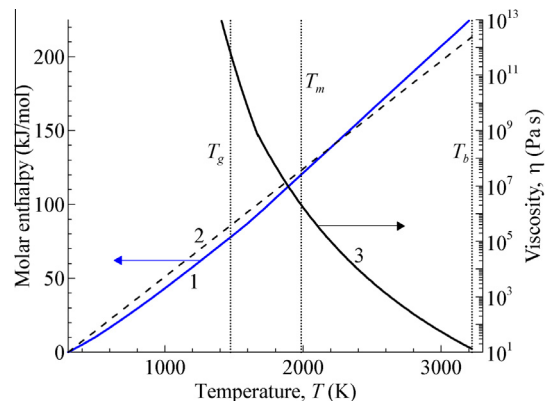


Fig. 2. Molar enthalpy (1 and 2) and dynamic viscosity η (3) of fused silica versus temperature T . Vertical dotted lines show the temperatures of glass transition T_g , transition to liquid T_m , and boiling T_b .

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