# Modelling of Selective Laser Melting Process of Quartz Glass at Elevated Temperatures

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**Abstract.** Selective laser melting (SLM) to date is the method of additive manufacturing allowing fabricating products from powder layer-by-layer according to a 3D model. However, when applying this method to fragile materials, parts crack while fabricating due to high temperatures. Quartz glass is a promising material for fabricating products by SLM without cracks due to a low thermal expansion. However, quality of fabricated material differs from the fused cast ones. This article aims to test the method of SLM with preheating to improve the material quality. Experiments on single track formation in SLM are analysed by modelling the coupled processes of heat transfer and powder consolidation in the laser-interaction zone. The mathematical model is validated by the experiments. It is shown that the preheating can improve the material quality and increase the process productivity but overheating may result in undesirable crystallization.

## 1 Introduction

The emerging 3D printing technologies can be advantageous for manufacturing components of glass. They do not require fabrication of exact molds necessary for die pressing of optical elements and can be applied to manufacture parts of complicated shape, for example hollow elements that are difficult to fabricate by conventional processes like die pressing [1]. Selective laser melting (SLM) is an additive manufacturing (3D printing) process consisting in layer-by-layer consolidation of a powder bed by a scanning laser beam that fuses powder particles together to form a solid part. Successful application of this material is demonstrated in specialized literature. Material does not contain cracks, however, pores remain inside the fused material [2]. In addition, the authors of the article [3] predict that consolidation can be improved provided that sample heating occurs while laser processing. The SLM was successively applied to borosilicate [4], soda-lime [5], and quartz [6] glass. The advantages of the process are flexibility and high precision. The disadvantages are residual porosity and stresses. In SLM, a portion of a powder bed is generally exposed to the laser beam for a fraction of a millisecond [3]. It can be insufficient for complete consolidation of powder and result in excessive residual porosity. The residual stresses arise because of a highly non-uniform temperature distribution in the laser-interaction zone, which launches thermo-mechanical processes [7].

Quartz glass is a promising material for SLM because of extremely low thermal expansion. That is why it does not crack in the conditions of a strong thermal shock at laser processing [6]. Consolidation of quartz glass powder is controlled by viscous flow at coalescence of molten powder particles [3]. Unfortunately, the viscosity of quartz glass is rather high even at elevated temperatures [8]. That is why the residual porosity can be unsatisfactory [3]. To reduce the porosity, one can reduce the scan speed at SLM [3]. This extends the thermal cycle, and thus increases the extent of consolidation. The disadvantage of such an approach is decreasing the productivity that is proportional to the scan speed. Another drawback is a strong non-uniformity of pore distribution in the laser-interaction zone. Even if the central domain is free of pores, a high porosity can be observed in the periphery of the heat affected zone where the temperature is lower and the viscosity is greater [3]. To attain a low and more uniform porosity and increase the productivity of SLM, it was proposed to apply a preheat [3]. The preheat is maintaining the working zone of the SLM machine at an elevated temperature during the whole process. It was successfully applied to other materials, for example to reduce cracking at SLM [9].

The present work aims to test experimentally the influence of preheating on SLM of quartz glass and to model the coupled physical processes of heat transfer and powder consolidation in the laser-interaction zone at SLM. The comparison of the experiments with the modelling is useful to analyze the influence of SLM process parameters on the quality of the resulting material.

## 2 Model and experiment

### 2.1. Mathematical model

This work uses a mathematical model of laser-influence zone on a layer of quartz glass powder at different process parameters of selective laser melting (such as

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laser power, scanning speed, layer thickness and preheat temperature). Heat transfer is calculated in this model by the following equation:

$$\partial H/\partial t=\nabla\cdot(\lambda_e\cdot\nabla T)+u\cdot\partial H/\partial x \quad (1)$$

where $H$ is the volumetric enthalpy, $\lambda e$ the effective thermal conductivity, ∇ the nabla operator, $t$ the time, $T$ the temperature, u the scanning speed, $x$ the longitudinal coordinate. Figure 1 shows scanning process.

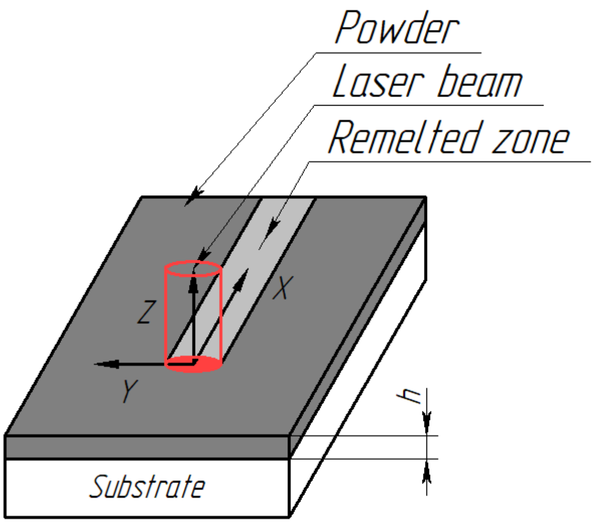


**Fig. 1.** Scanning process

Also enthalpy is related with temperature by the following equation [2+]:

$$H=(1-\varepsilon)C_pT \quad (2)$$

where $\varepsilon$ is the porosity equal to the volume fraction of the gas phase, and $C_p$ the volumetric specific heat.

Effective thermal conductivity is calculated by the following equation [3]:

$$\lambda_e=\lambda_s\xi(1-\varepsilon)N/\pi \quad (3)$$

where $\lambda_s$ is the thermal conductivity of solid phase, $N$ the average coordination number, $\xi=a/D$ the consolidation degree meaning that the softened particles of fused silica behave like the droplets of viscous liquid. They tend to coalesce as shown in Fig. 2. 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 [3] calculated by the following equation [3]:

$$(\partial\xi^2)/\partial t=3\delta/(\eta D) \quad (4)$$

where $D$ is the particle diameter, $\delta$ the surface tension coefficient, $\eta$ the dynamic viscosity. The efficiency of this model has been demonstrated in Ref. [3] and has been proven with our experiments.

The mathematical model considers laser radiation influence on a single layer and the substrate because every single layer becomes substrate for previous ones in the technology of SLM. Scanning of the surface by a laser beam occurs in a straight line at a constant speed $u$. The thermal conditions of laser scanning can be different for initial stages of consolidation, however, eventually all processes become steady.

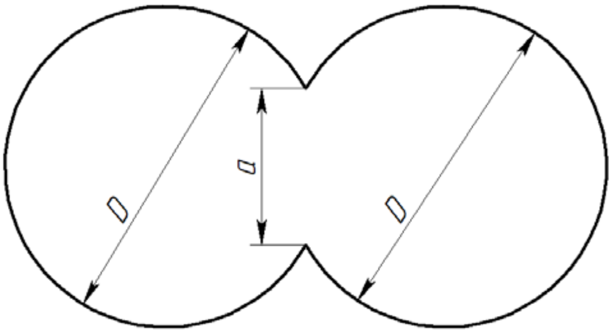


**Fig. 2.** Coalescence of two spherical particles of diameter D with formation of a neck of diameter a.

According to predictions made in Ref. 1, the laser radiation is absorbed on the surface of the target. This gives a heat flux through plane $z = 0$ with the density distribution equal to the energy density flux in the cross-section of the laser beam [3]:

$$q_0=P_0\cdot\exp(-r^2/r_0^2)/(\pi\cdot r_0^2) \quad (5)$$

where $P_0$ is the absorbed power of the laser beam, $r_0$ its nominal radius, and $r^2 = x^2 + y^2$.

Also this model considers heat losses from sample's surface due to evaporation. The Model proposes evaporation speed as function of surface temperature, boiling point $T_b$, latent heat of evaporation $Q_b$ and vapour molecular mass. Heat losses on evaporation can be evaluated the mass loss multiplied with the latent heat of evaporation.

All necessary parameters are shown in Table 1 [2], [3].

**Table 1.** Calculation parameters.

| Name | Letter | Value |
|---|---|---|
| Boiling point | $T_b$ | 3223 K |
| Latent heat of evaporation | $Q_b$ | 9.6 MJ/kg |
| Porosity | ε | 0.4 |
| Mean coordination number | $N$ | 7.1 |
| Particle diameter | $D$ | 20 μm |
| Solid phase thermal conductivity | $\lambda_s$ | 2.2 (W/m*K) |
| Layer thickness | $h$ | 0.2 mm |
| Volumetric specific heat | $C_p$ | 2.68 MJ/(m$^3$K) |

## 2.2. Experiment

In this work, we made experiments with silica glass powder with fraction 80-100 microns. The substrates are plates of quartz glass TU-21RSFSR-644-83 with non-polished surface of thickness 5 mm.

Laser $CO_2$ source provides 10.6 micron wavelength in continuous mode which quartz absorbs. The source is integrated in commercial engraving machine Qualitech 203 mini. Also, a heater is integrated by our team in this machine. The scheme of the experimental setup is shown in Fig.3 laser beam 2 from sealed $CO_2$ tube 1 is deflected by fixed mirror 3 and moving mirror 4 that is standing on the support moving at X axis. Laser head 5 moves along this rail in Y direction. The laser head contains a mirror at the top and a ZnSe lens of 2 inches focal length on the bottom. Target 6 is mounted in the heater 7 for making samples preheat. Metallographic microscope Olympus BX51M is used for getting photos of samples.

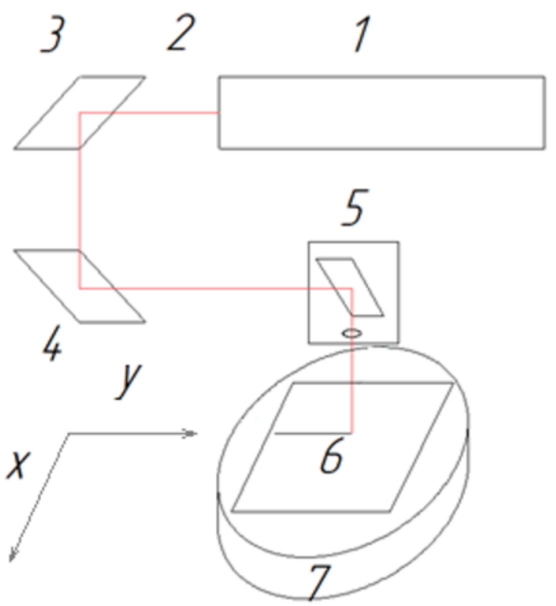


**Fig. 3.** Principal scheme of laser engraving machine Qualitech 203 mini.

## 3 Results and discussion

Figure 4 presents the results of calculation. As we can see, the heat affected zone in SLM often become bigger than the powder layer thickness. Thereby, powder sinters with the previous layer. However, using only laser processing is sometimes not enough for good sintering with the substrate. Preliminary heating of the sample is perspective for attaining high consolidation. Figure 5 shows comparative results of the consolidation degree.

As one can see, the influence of preheat is not only elevated temperatures, it is also a better sintering due to the decreasing of viscosity with temperature. However, we can also try to predict more effective parameters of scanning. In our case, other parameters such as the layer thickness, the scanning speed and the beam power can be changed

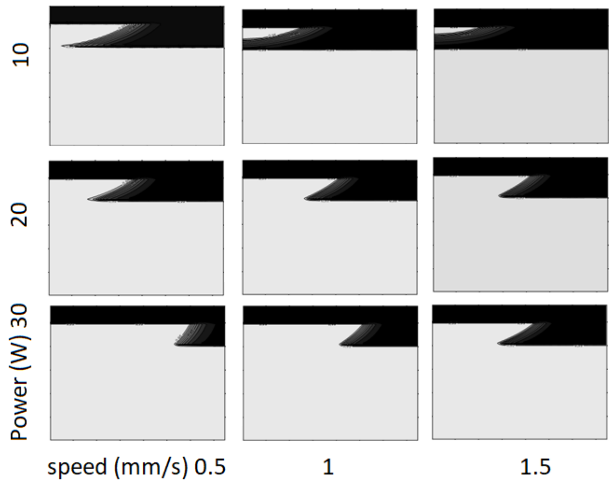


**Fig. 6.** Comparative results of modelling consolidation degree (white means ξ >0.9) of nine different situations with have different changing parameters: from top to bottom power changes from 10 to 30 W, from left to right scanning speed changes from 0.5 to 1.5 mm/s. Ambient temperature is 1100 K.

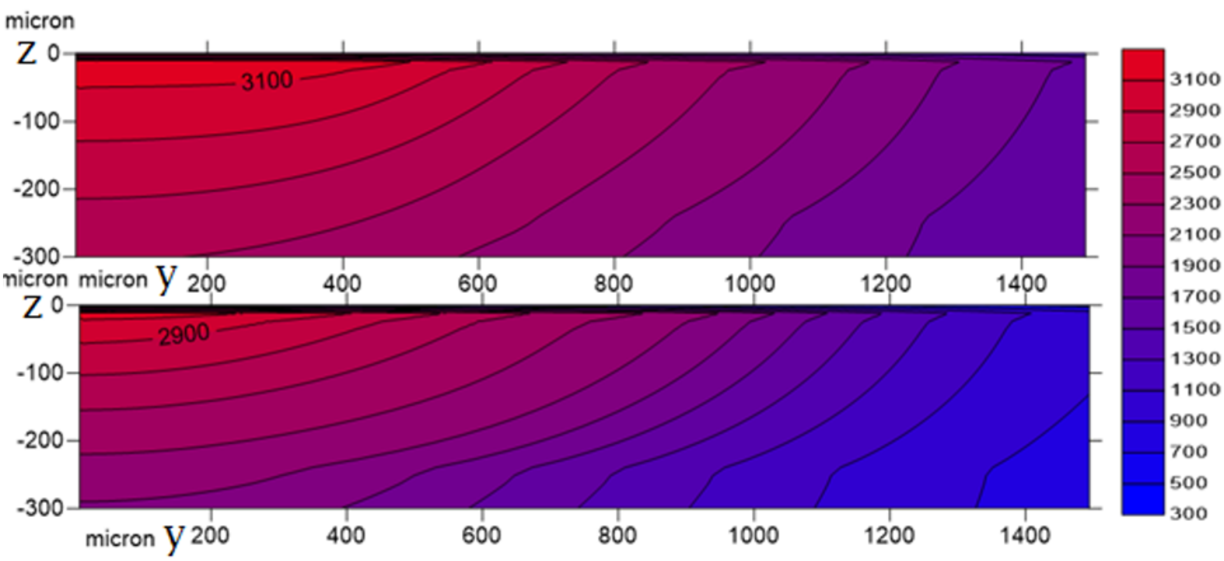


**Fig. 4.** Distribution of the maximum temperature (K) attained in the transversal cross section (YZ) for the modeled processes of laser melting of glass. On the top, processes modeled with ambient temperature = 1100 K. Below, ambient temperature = 300

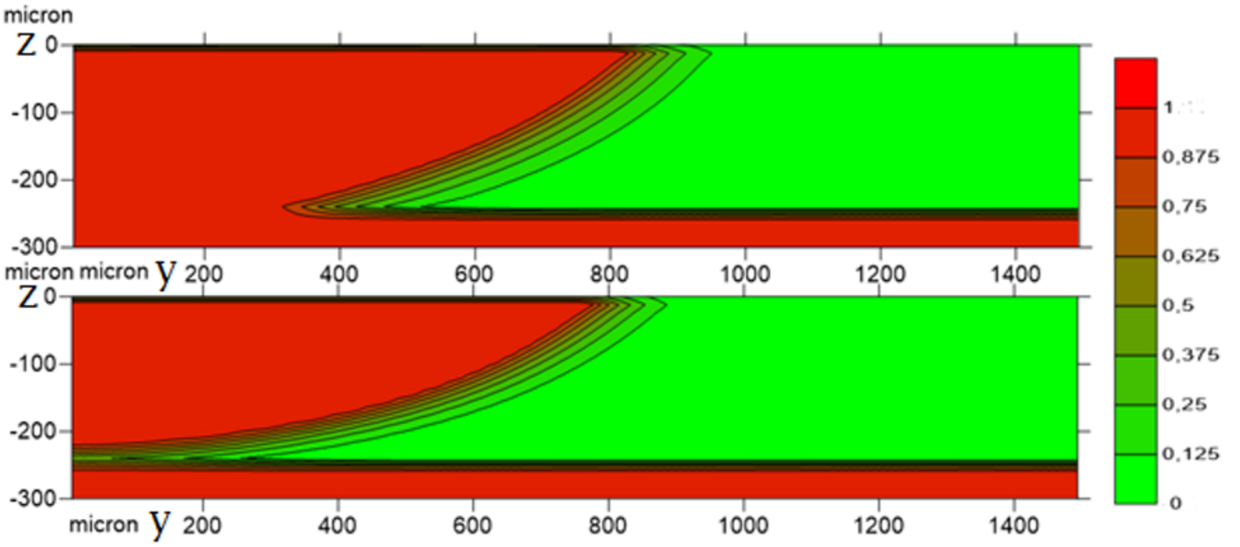


**Fig.5.** Sintering degree (χ2) for the modeled processes of laser melting of glass. On the top,ambient temperature = 1100K. Below, ambient temperature = 300 K.

Figure 6 shows the influence of changing the scanning speed and beam power. The 10 W beam power cannot be used in our case because it gives bad sintering results, but we can use 20 or 30 W and the difference there is not as big as between 10 and 20 W. We can also see that scanning speed influence is bigger for 30 W laser power. We can make conclusion that 30 W and 0.5 mm/s is the most effective mode.

After getting modelling results, we made some experiments with fused silica powder according to them. Figure 7 presents sintering tracks. Figures 8 and 9 present cross section of these tracks.


**Fig. 7.** Top view of the tracks made at scanning speed = 1 mm/s and power = 20 W (left) and 30 W (right), preheat temperature 1100K, layer thickness 200 microns.

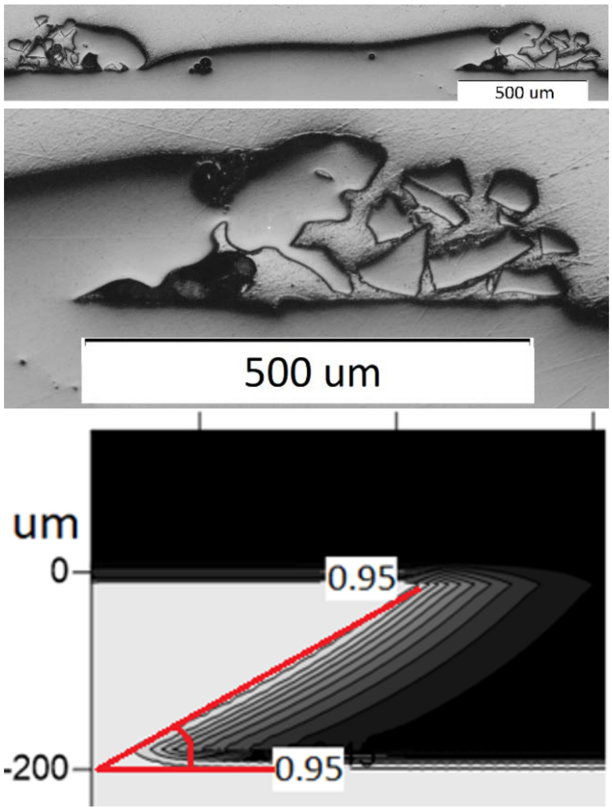


**Fig. 8.** Cross section of tracks made at 1 mm/s 20 W(on the top) same zoomed track (in the middle) and the modelling (on the bottom). The red lines show the angle between the substrate and the consolidation border.

As one can see in Figs. 8 and 9, this calculation method works even with elevated temperatures. At 20 W beam power, we can see similar angle between substrate and sintered material in calculations and in experiments. At 30 W beam power, we also can see this angle. The angle between the substrate and consolidation border increases when power increases.

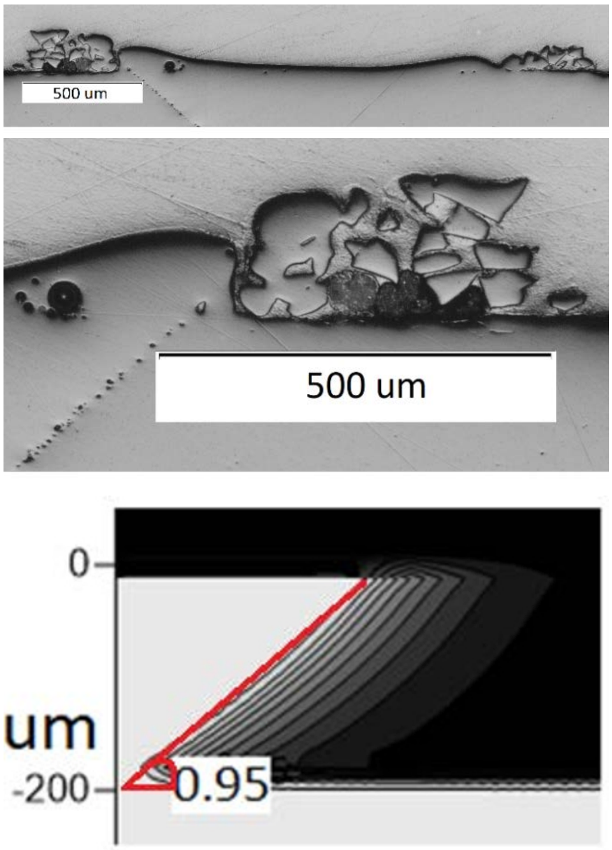


**Fig. 9.** Cross section of tracks made at 1 mm/s 30 W(on the top) same zoomed track (in the middle) and his modelling (on the bottom). The red lines show the angle between the substrate and the consolidation border.

Also at 30 W we predict that we got visible cristobalite (turbid track in Fig.7. right) because in [10] authors show results of quartz crystallization with transformation into crystobalite experiments and describe it [10]. It cannot be tridymite because the used silica glass powder is clean [11]. Getting crystobalite means that we reached temperature above the crystallization one for a time interval enough to crystallization [10]. The preheating temperature must be lower than the glass transition temperature, otherwise glass will not form after cooling the melt obtained by laser treatment. Laser heating of glass in the crystallization interval must be for a short term, otherwise the glass will devitrify. The numerical values of the characteristic temperatures are shown in Table 2. The preheat temperature 1100 K used in this work is less than both the glass transition temperature and the minimum crystallization temperature. However, the laser treatment results in formation of a heat affected zone in the periphery of the laser-interaction zone where the temperature is within the crystallization range (see Fig. 4). This may initiate crystallization observed as turbid domains in Fig. 7.

## 4 Conclusions

A mathematical model is proposed to describe interdependent processes of heat transfer and powder consolidation at selective laser melting (SLM) of quartz glass. The model is validated by comparison with experiments on formation of single tracks. Numerical calculations indicate that the preheating accelerates powder consolidation. This result is in line with experiments. Thus, the preheating is favourable to increase the productivity of SLM and to improve the quality of the material. However, quartz glass can crystallize at a too high preheat temperature.

**Table 2.** Temperatures of glass transition and crystallization.

| Name | Value | Ref. |
|---|---|---|
| Glass transition temperature | 1475 K | 3 |
| Crystallization interval | 1273-1923 K | 10 |

This work was supported by the Russian Science Foundation, grant #20-79-00274.

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