Corrected

Prof./Ens. Boillat-Brugger-Moser - Introduction to AM

Date 26.01.2019 - duration : 3h00

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Open Book Part

Name :

Wait for the beginning of the test before turning the page. This document is printed double-sided, it contains 15 pages, the last ones can be empty. Do not remove the staple.

- Put your student card on the table.
- Any document is allowed.
- The use of a computer or of a cell phone is prohibited during the test.
- After the exam, the teachers reserve the right to cancel any questions which they will consider to be ill-posed.
- Write your name on every page

Question	Number of points
1)	
2)	
3)	

Question 1: *This question is scored on 30 points*

You apply the SLM process to manufacture parts out of a bronze powder characterized by the follwing thermal and mechanical properties:

Table 1: Thermal/mechanical properties of the bronze material

therm. conduc. k, W/mm/K	e.m. absorpt. $A@\lambda = 1070\,\text{nm}$	density ρ, g/mm^3	heat capacity C_p, J/g/°C	melting temp. T_melt,°C	latent heat L_f, J/g
0.170	18%	8.72×10^{-3}	0.380	1005	214

Your SLM machine is to be equipped with an Ytterbium fiber laser ($\lambda = 1070\,\text{nm}$) emitting a quasi top-hat (uniform) beam of quality $M^2 = 17.8$.

a) The power P_0 needed to melt the powder is a function of the scan speed v and of the radius w_f in the focal plane (=surface of the powder bed). For which value of v and w do we get the **minimal** value of P_0? Justify your answer.

Solution

For a quasi top-hat beam, the intensity must satisfies

$$I_0 \geq \frac{k(T_\text{melt} - T_\text{amb})}{A w_\text{f}} \times \frac{1}{H(\frac{v w_\text{f}}{2\eta})} \tag{1}$$

otherwise the material will not melt. In equation (1), H is a real function of one variable and T_amb denotes the room ambiant temperature.

The power is obtained by integrating the intensity. For a top-hat beam we have $P_0 = I_0 \pi w_\text{f}^2$ which means by (1) that

$$P_0 \geq \pi \frac{k(T_\text{melt} - T_\text{amb}) w_\text{f}}{A} \times \frac{1}{H(\frac{v w_\text{f}}{2\eta})}.$$

For a fixed value of w_f, P_0 only depends on v through H which is a decreasing function of its argument s starting from value $H = 1$ at $s = 0$. It means that a **zero velocity** will always minimizes the power.

If the velocity is zero, then P_0 only depends on the radius w_f:

$$P_0 \geq \pi \frac{k(T_\text{melt} - T_\text{amb}) w_\text{f}}{A}. \tag{2}$$

This dependance implies a linear growth of the power with respect to w_f. Consequently the radius has to be chosen **as small as possible**.

b) You use a lens to focus the Ytterbium fiber laser described above. What is the minimal possible value of the focal waist w_f you can expect?

Solution

With an optimal optical chain, the beam waist that can be achieved in the focal plane is obtained form the focusing limit formula:

$$w_{\mathrm{f}} \geq \lambda M^2 \simeq 1.07 \times 17.8 \simeq 19.05\,\mu\mathrm{m}$$

c) You combine the fiber laser with a converging lens with focal length $f = 720\,\mathrm{mm}$ and radius $R = 50\,\mathrm{mm}$. Using this additionnal information, estimate the minimum power P_0^{min} which is required to melt the powder.

Solution

The optical chain we have has a $f-$number of $\frac{f}{2\pi R} \simeq \frac{720}{2\times 3.14\times 50} \simeq 2.3$, Therefore the beam waist we will get will be

$$w_{\mathrm{f}} \simeq \lambda M^2 \frac{f}{2\pi R} \simeq 19.05 \times 2.3 \simeq 43.66\,\mu\mathrm{m} \tag{3}$$

If we substitute this value in (2) and use the numerical data to express the other quantities, we get

$$P_0 \geq \frac{3.14 \times 0.170 \times (1005 - 20) \times 0.04366}{0.18} \simeq 127.6\,\mathrm{W}.$$

d) You select the laser power by multiplying P_0^{min} with a security factor of 1.5 and by rounding the result to the upper hundred. Give an estimate of the maximum consolidation rate you can obtain.

Solution

The secure value of the power you choose is $P_0 = 200\,\mathrm{W}$. Since the energy needed to melt a unit of volume of material from ambiant temperature $T_{\mathrm{amb}} \simeq 20°$ is

$$\eta\rho(C_p(T_{\mathrm{melt}} - T_{\mathrm{amb}}) + L) \simeq 8.72 \times 10^{-3} \times (0.38 \times (1005 - 20) + 214)$$

i.e $\eta \simeq 5.13\,\mathrm{J/mm^3}$, the maximum consolidation rate that can be obtained, if there are no losses (conduction, convection, radiation, ...), is

$$\max \mathrm{MCR} = \frac{AP_0}{\eta} \simeq \frac{0.18 \times 200}{5.13} \simeq 7.01 \mathrm{mm^3/s}. \tag{4}$$

e) The hatching distance h to be used can only be selected among a discrete number of choices:

Table 2: Possible hatching distance

choice No	1	2	3	4	5	6
h μm	0.00107	0.10700	1.07000	10.0000	80.0000	1000.00

Is one on these choices adequate? If yes tell which one, if not explain why and make a smart suggestion for h.

Solution

The hatching distance should be of the order of magnitude of the beam diameter, to ensure a correct overlapping. Since the beam diameter d is two times the beam waist $w_\mathrm{f} \simeq 43.66\,\mu$m (3), we have $d \simeq 87.32\,\mu$m which means that the hatching distance no 5, $h = 80\,\mu$m is the best choice.

f) Assume that the layer thickness is $e = 30\,\mu$m and that the hatching distance h is chosen according to what has been said in e). Under these conditions, determine the velocity to be used to achieve the maximum consolidation rate estimated in d).

Solution

The fomula linking the material consolidation rate MCR to the scan speed v, the hatching distance h and the layer thickness e is

$$\mathrm{MCR} = hev.$$

Solving for v and using the numerical value, we get

$$v = \frac{\mathrm{MCR}}{he} \simeq \frac{7.01}{0.08 \times 0.03} \simeq 2'924\,\mathrm{mm/s}.$$

g) Determine the maximum temperature reached in the powder bed if we apply the scan velocity calculated above. Compare the obtained value to the melting temperature. What do you observe and how do you explain it?

Solution

The maximum temperature increase ΔT under the top-hat laser beam depends on the material properties and on the processing parameters:

$$\Delta T = \frac{AP_0}{\pi k w_\mathrm{f}} H\left(v \frac{\rho C_\mathrm{p} w_\mathrm{f}}{2k}\right).$$

With the numerical value, we get

$$\Delta T = \frac{0.18 \times 200}{3.14 \times 0.17 \times 0.0436} H \left(2'924 \times \frac{8.72 \times 10^{-3} \times 0.38 \times 0.0436}{2 \times 0.17} \right).$$

$$\Delta T \simeq 1544 \times H(1.243).$$

As it can be seen from the graphics in the lecture note, the value $H(1.243)$ in case of a top-hat beam is around 0.65. Therefore, we will have

$$\Delta T \leq 1544 \times 0.65 \simeq 1003.6^{\circ}$$

which effectively corresponds more or less to melting ($T_{\mathrm{melt}} \simeq 1005^{\circ}$) if we start from ambiant temperature $T_{\mathrm{amb}} \simeq 20^{\circ}$.

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Question 2: *This question is scored on 15 points*

a) Fig. 1 represents a known additive process. Give its acronym and its complete name.

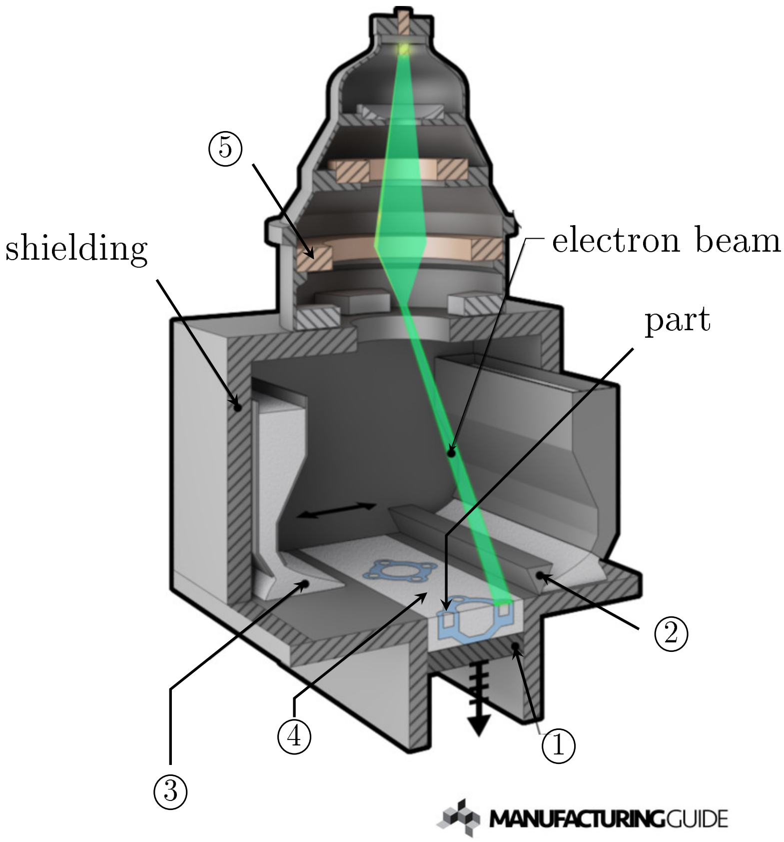

Figure 1: Schematic representation of an additive process

Solution

Electron **B**eam **D**irect **M**anufacturing (EBDM)

b) In Fig. 1, five elements are not named but numbered 1-5. Describe those items below:

1: Construction table

2: Rake for powder compaction

3: Hopper with powder

4: Powder bed

5: Magnetic deflectors/lenses

c) In Fig. 1 it can be observed that the shielding is thick. What is the reason behind it?

Solution
The interaction of an electron beam with a metallic material produces X-Rays. This emission is dangerous for health and the role of the thick shielding is to absorb it.

d) Explain briefly which physical mechanism(s) are used in the process of Fig. 1 to achieve consolidation.

Solution
The consolidation mechanism of EBDM is liquid phase bounding:

i) The powder material **absorbs** a part of the electron beam energy and turns it into heat.
ii) The heat raises the powder temperature and leads finally to **melting**.
iii) The melt pool **wets** the already consolidated part. It is bound to it after **cooling**.

e) Is it possible to apply the process of Fig. 1 to polymer or to ceramic materials? Justify your answer.

Solution
Since an electron beam is **not efficiently absorbed** by a **non-conductive** material, most ceramics and polymers cannot be processed.

f) Is the process of Fig. 1 a direct (leading directly to the part in the right material) or an indirect additive process?

Solution
The process **is direct**. The as-built part is homogenous and made 100% out of the **right** material. In particular there is **no binder** in the as-built part which would have to be eliminated by thermal post-processing.

g) Name at least **two** different additive processes using the **same** base material as the process of Fig. 1. For each, precise if it is a direct or an indirect process.

	Process name and acronym	**direct**	**indirect**
1)	SLM	X	
2)	Binder deposition		X

h) In which country has the process of Fig. 1 been developed and industrialized (**Hint**:*this country is also known for producing matches* ☺)

Solution

In Göteborg, Sverige

Question 3: *This question is scored on 23 points*

a) The part in Fig. 2 represents a bearing with an internal lubrication system. It contains a particular feature wich makes additive process well adapted for its fabrication. Describe this feature and justify your answer below:

Solution

The **internal lubrication system** is not possible to do with traditional machining unless we accept to fabricate the part as an assembly of different sub-parts. AM enables fabrication **without assembly**.

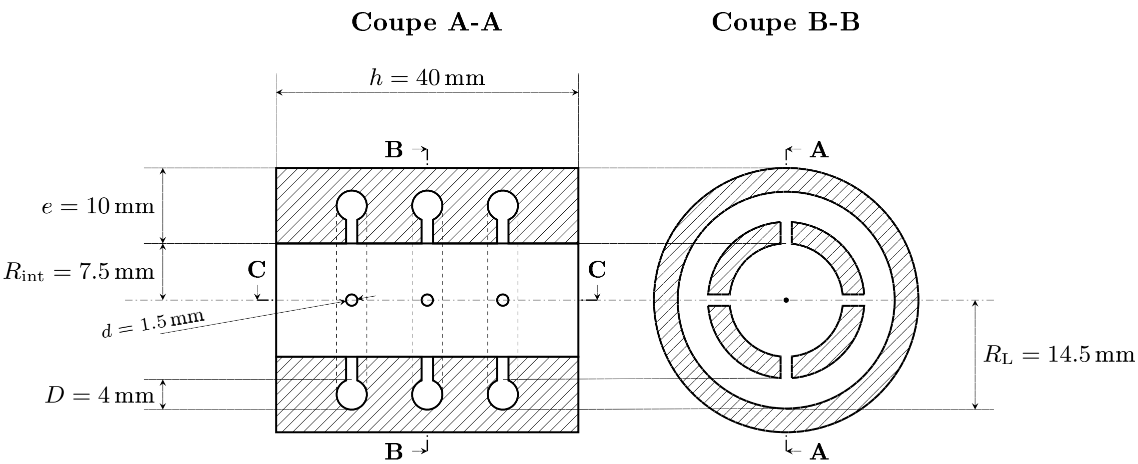

Figure 2: Drawing of the part to be produced, with dimensions of utilization

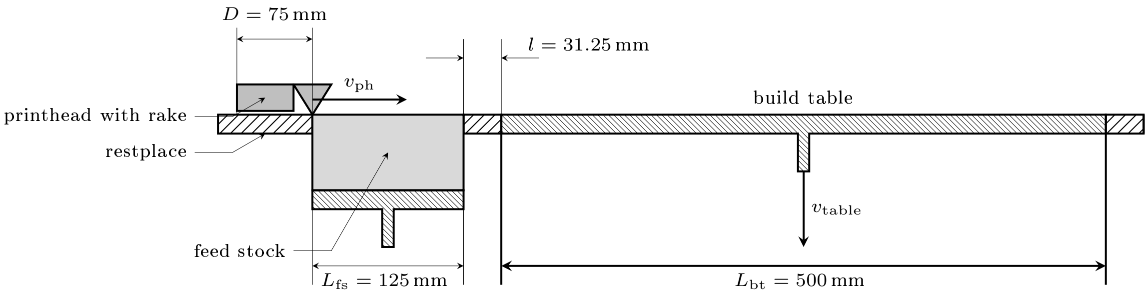

Figure 3: Schematic representation of the Digital Metal™ machine

b) Whithout this feature, the part would certainly be easy to manufacture by traditional processes. Name at least one such process which could be applied in that case.

Solution

Bar turning or **extrusion** are good options. Taking the application into account, extrusion would certainly required post-processing like grinding.

c) As a first manufacturing option, you select the Digital Metal^{TM} process by the Swedish company Höganäs (see Fig. 3). In which categorie of additive processes does this particular process belong?

Solution

Binder jetting belongs to the **powder based processes** categorie and it is an **indirect** process when applied to metals.

d) The other option for fabricating the part is the SLM process (see Fig. 4).

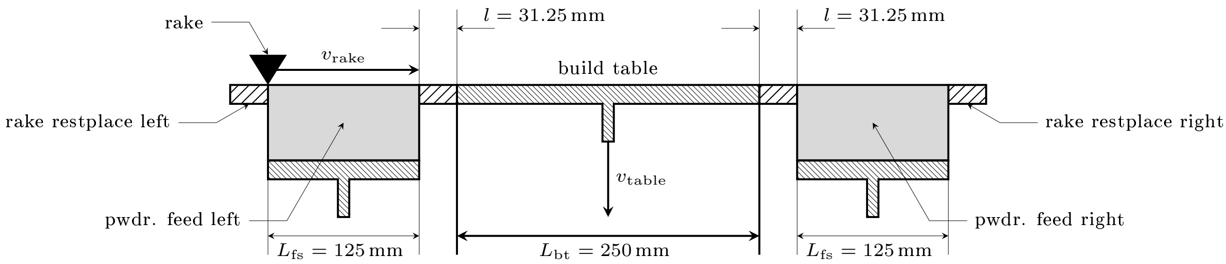

Figure 4: Representation of the SLM machine

Your first intention is to base your final decision on the fabrication time. The tables below give you numerical information about the process parameters to be applied on the two different machines:

Table 3: Process parameters to apply on the SLM machine

table speed	**rake speed**	**scan speed** laser on	**scan speed** laser off	**hatching distance**	**layer thickness**
$0.1\,\text{mm/s}$	$40\,\text{mm/s}$	$1000\,\text{mm/s}$	very large	$75\,\mu\text{m}$	$50\,\mu\text{m}$

Table 4: Process parameters to apply on the Digital Metal^{TM} machine

table speed	**printhead speed** homing motion	**printhead speed** printing motion	**layer thickness**
$0.4\,\text{mm/s}$	$150\,\text{mm/s}$	$75\,\text{mm/s}$	$50\,\mu\text{m}$

Have you enough information to compute the layering time and the MCR for each process? If yes fill the following table (value and corresponding unit, explain your calculation on the pages at the end of the exercise):

Solution

Table 5: Layering time and MCR

Process	**SLM**	**Digital Metal^{TM}**
layering time	$14.5625\,\mathrm{s}$	$13.25\,\mathrm{s}$
MCR	$3.75\,\mathrm{mm^3/s}$	$\infty\,\mathrm{mm^3/s}$

- The layering time for SLS is the time needed to move down the table and to let the rake goes from its homing position on one side to its homing position at the other side. The table motion is $h = 0.05\,\mathrm{mm}$ with a speed $v_{\mathrm{table}} = 0.1\,\mathrm{mm/s}$ and the rake travels over a distance of $\ell = 562.5\,\mathrm{mm}$ at a speed $v_{\mathrm{rake}} = 40\,\mathrm{mm/s}$. We get

$$\tau_{\mathrm{layer;SLM}} = \frac{h}{v_{\mathrm{table}}} + \frac{\ell}{v_{\mathrm{rake}}} = \frac{0.05}{0.1} + \frac{562.5}{40} = 14.5625\,\mathrm{s}.$$

- The layering time for Digital Metal^{TM} is the time needed to move down the table and to let the print-head goes from its homing position on the left to the far right and to come back to its homing position. The table motion is $h = 0.05\,\mathrm{mm}$ with a speed $v_{\mathrm{table}} = 0.4\,\mathrm{mm/s}$ and the printhead travels two times over a distance of $\ell = 656.25\,\mathrm{mm}$ first at a speed $v_{\mathrm{print}} = 75\,\mathrm{mm/s}$ and then at a speed $v_{\mathrm{home}} = 150\,\mathrm{mm/s}$. We get

$$\tau_{\mathrm{layer;DM}} = \frac{h}{v_{\mathrm{table}}} + \frac{\ell}{v_{\mathrm{print}}} + \frac{\ell}{v_{\mathrm{home}}} = \frac{0.05}{0.4} + \frac{656.25}{75} + \frac{656.25}{150} = 13.25\,\mathrm{s}$$

- The material consolidation rate of SLM is obtained as the product of the scan speed, the hatching distance and the layer thickness:

$$\mathrm{MCR_{SLM}} = vhe = 1000 \times 0.075 \times 0.05 = 3.75\,\mathrm{mm^3/s}.$$

- There is no consolidation time in a binder deposition process (volume has no influence on build time). It means that

$$\mathrm{MCR_{DM}} = \infty.$$

e) Assume that the build direction is the axis of symmetry of the bearing and use the results obtained in Tab. 5 to compute the fabrication time (per part) for each process and for different batch sizes (write the details of calculation at the end of the exercise):

Solution

Table 6: Fabrication time per part

	SLM	**Digital Metal^{TM}**
1 part:	05h 20min 38s	02h 56min 40s
10 parts:	02h 25min 53s	00h 17min 40s

- The number of layers to build is

$$N_{\mathrm{layer}} = \frac{h}{e} = \frac{40}{0.05} = 800.$$

- The deposition time for the SLM process is

$$t_{\text{dep;SLM}} = N_{\text{layer}}\tau_{\text{layer;SLM}} = 800 \times 14.5625 = 11'650\,\text{s}. \tag{5}$$

- The deposition time for the Digital Metal$^{\text{TM}}$ process is

$$t_{\text{dep;DM}} = N_{\text{layer}}\tau_{\text{layer;DM}} = 800 \times 13.25 = 10'600\,\text{s}. \tag{6}$$

- Since there is no consolidation time in the Digital Metal$^{\text{TM}}$ process the fabrication time for one part corresponds to the deposition time (6) mutualized over the batch size (provided all the parts fit on the construction platform!):

$$t_{\text{build;DM;1p}} = t_{\text{dep;DM}} = 10'600\,\text{s} = 2\,\text{h}\,56\,\text{min}\,40\,\text{sec}.$$

$$t_{\text{build;DM;10p}} = t_{\text{dep;DM}}/10 = 1060\,\text{s} = 17\,\text{min}\,40\,\text{sec}.$$

- In SLM, the volume of the part influences the build time. The volume of the bearing (including the internal lubrication structure) is

$$V_{\text{ext}} = h(\pi(R_{\text{int}} + e)^2 - \pi R_{\text{int}}^2).$$

It means that

$$V_{\text{ext}} \simeq 40 \times (3.14 \times 17.5^2 - 3.14 \times 7.5^2) \simeq 31'416\,\text{mm}^3$$

The volume of one single internal lubrication structure (we neglect the hole connecting it to the shaft) is

$$V_{\text{L}} = 2\pi(R_{\text{L}} - \frac{D}{2})\pi\frac{D}{2}^2$$

that is

$$V_{\text{L}} \simeq 2 \times 3.14 \times (14.5 - 2.0) \times 3.14 \times 2.0^2 \simeq 987\,\text{mm}^3.$$

The volume of the part is therefore

$$V = V_{\text{ext}} - 3V_{\text{L}} \simeq 28'455\,\text{mm}^3.$$

The consolidation time for one part is

$$t_{\text{cons;SLM;1p}} = \frac{V}{MCR} \simeq \frac{28'455}{3.75} = 7'588\,\text{s}. \tag{7}$$

- The build time of one part is obtained by adding the consolidation time (7) to the deposition time (5) mutualized over the batch size (provided all the parts fit again on the construction platform!):

$$t_{\text{build;SLM;1p}} = 7'588 + 11'650 = 19'238\,\text{sec} = 5\,\text{h}\,20\,\text{min}\,38\,\text{sec}$$

and

$$t_{\text{build;SLM;10p}} = 7'588 + 1'165 = 8'753\,\text{sec} = 2\,\text{h}\,25\,\text{min}\,53\,\text{sec}.$$

Hint: *The volume of a torus is the volume of a cylinder with equivalent section and a height equal to the perimeter of the circle joing the centers of the sections.*

f) The internal surface of the bearing has to be smooth (N7 standard: $R_{\text{a}} \simeq 1.6\,\mu\text{m}$) and to resist to deformation (Young modulus E at least as high as 200 GPa). Are the two additive processes

(SLM and Digital Metal^{TM}) able to deliver a part with such properties? If not, fill the following table with the list of the postprocessing steps which will be needed:

Solution

Table 7: Needed postprocessing

SLM	**Digital Metal^{TM}**
machining	debinding
thermal treatment (hardening)	oven sintering
grinding	inflitration
-	machining/thermal treatment
-	grinding

g) In case you select the Digital Metal^{TM} is that true that you have to produce the fabrication file (.stl file) by respecting exactly the dimensions of utilization given in Fig. 2? If it is not the case, justify your answer and explain how the dimensions have to be modified.

Solution

The .stl file should anticipate the material **shrinkage** which will mostly be due to the post-processing (sintering). The dimensions of the part in ths .stl will be the corresponding utilization dimensions time **a factor** > 1 which can be up to $1.25 - 1.30$.

h) You would like to decrease the diameter d of the lubrication holes. Is it possible to make this quantity as small as you want, or, due to manufacturing reasons, is there a limit under which you cannot go? If it is the case, please justify your answer.

Solution

i) A natural limitation is the process resolution linked to powder grain size and to laser spot size (SLM) or printhead pixel size (Digital Metal^{TM}). In general this limitation is $d \gg 0.1\,\mathrm{mm}$

ii) A more strict limitation is due to the fact that we have to be able to **empty the internal lubrication system** from all the loose powder it contains, at the end of the fabrication.
The only way to remove the emprisoned powder is **to bring it out by the hole of diameter** d. For typical powder, a hole of $d = 1.5\,\mathrm{mm}$ might already be an issue and leads to blocking.