PROJECT IN ADVANCED MANUFACTURING I (ME5600A)

SUBMITTED BY

LIN KANG (A0191818W)

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Contents

1. Introduction of melt pool analysis

1.1 Selective laser sintering

Early additive manufacturing equipment and materials were developed in the 1980s. Additive manufacturing is based on the three-dimensional data of the model and controlled by the computer, so that the material can be formed layer by layer. 3D printing technology has the advantages of fast manufacturing speed, not limited by the shape of manufacturing parts, and so on. It is a very promising manufacturing technology that meets the future development trend.

Selective laser sintering (SLS) is a process of sintering powder material, usually polymeric due to low power of the lasers, into the solid products layer by layer, which may need debinding and heat treatment. In these additional steps, the components are treated to improve the mechanical properties since the process of SLS and the binder used by machine weaken the ceramic. The SLS process is carried out in vacuum or in the atmosphere, such as air, argon and nitrogen.

On the other hand, selective laser melting uses the powerful laser to make the original materials achieve a full melt, which means that the powder is not merely fused together but is melted into a homogenous part. The main difference between SLS and SLM is that the melting process fully heat the material to the melting temperature and the sintering process heat the material to the point that the powder can fuse together on a molecular level. Because of that, SLM is mainly used to produce a mono material, since mono material has only one melting point and the SLM process could melt the material up to this point and finally melt it.

The main process of SLS/SLM is shown in fig.1.

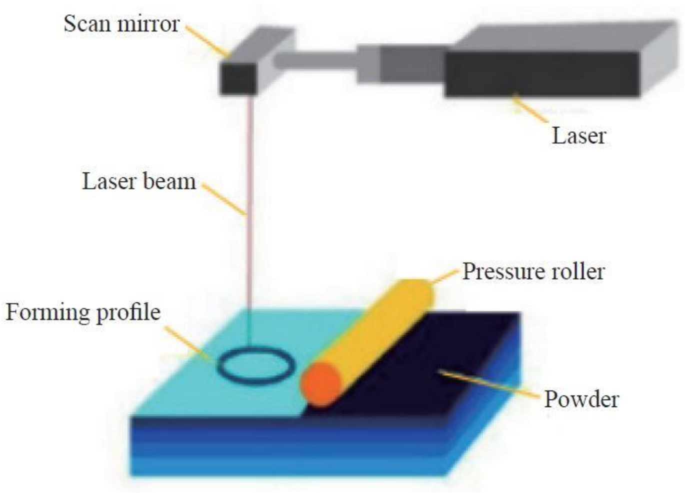


Fig.1 Schematic diagram of selective laser sintering/melting technology

a) Design CAD model of parts on the computer and use specific software to transform the model to STL (slicing the 3D model with plenty of horizontal planes). The computer obtains the required data from each thin layer and converts the data into control instructions for the laser beam scanner.
b) First, the powder cylinder rises, and the model cylinder descends. The roller pushes the powder horizontally from one side of the powder cylinder to the left edge of the model cylinder, and the roller moves forward with rotating backwards and vibrating until the roller reaches the right edge of the model cylinder. In this way, the powder can be spread evenly.
c) Then the model cylinder rises so that a portion of the newly laid powder rises above the table surface. The roller is reversed to its starting position by forward rotation. This process compacts the powder. The thickness after powder compaction should be equal to the thickness required by the corresponding STL model slice thickness.
d) The computer-controlled laser beam scanner scans and sinters according to the numerical control instructions provided in the first step.
e) Repeat the step b and step c until finish the whole manufacturing.

f) For indirect process, the final product need debinding and heat treatment and most of SLM process don’t need this process since there are binders in the final product produced by SLS machine.

1.2 Literature review

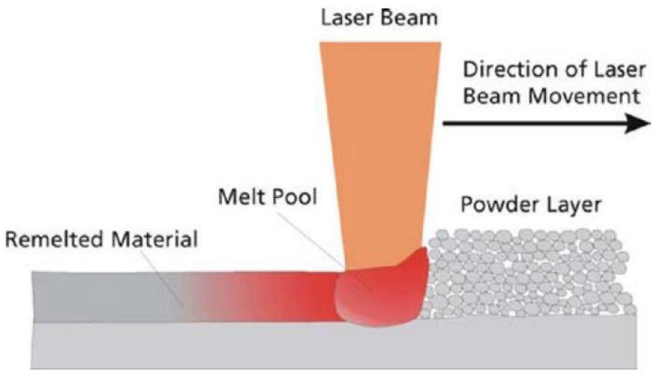


Fig.2 Schematic illustration of the laser melting process

In selective laser sintering process, there are still a lot of problems to solve and people have made some researches to overcome these barriers. Tom Craeghsa focused on the feedback control in this field. [2] They found that not only the process parameters such as laser power and scan speed should be designed to get a better products’ density and property, but also the melt pool variables could affect the surface quality. Further they also design a new feedback controller with the optimal signal feedback since in the experiment result they found the dynamic relation between the optical signal and the laser power which may finally determine the property of parts. Foster B used the layer wise optical image capture and analysis techniques to detect the defects of the final products. [3] Sam Coeck use the ‘DMP Meltpool’ software to monitor the melt pool data. With the analysis, they find that there exists a relationship between the final part porosity detected by the CT scanner and the melt pool data. Also, the melt pool data may reflect the static tensile properties with the observed melt pool monitoring signals. [3]

2. EOS machine and software introduction

2.1. Introduction of EOS M290

Fig.3 The figure of EOS M 290

The EOS M 290 is an industrial 3D printer made by the German manufacturer EOS which is based on the DMLS (Direct Metal Laser Sintering) 3D printing technology developed by EOS. This 3D printing technique uses a fiber laser to melt and fuse fine metal powder. Layer after layer the 3D object is built. This 3D printing method allows to create 3D printed products with complex geometries including elements such as freeform surfaces, deep slots and coolant ducts. This is the main working machine that I mainly focus on. The sheet below lists the main technical data of EOS M 290.

EOS M 290	
Building volume	250 mm x 250 mm x 325 mm (9.85 x 9.85 x 12.8 in)
Laser type	Yb-fiber laser; 400 W
Precision optics	F-theta-lens; high-speed scanner
Scan speed	up to 7.0 m/s (23 ft./sec)
Focus diameter	100 µm (0.004 in)
Power supply	32 A
Power consumption	max. 8.5 kW / typical 3.2 kW

Nitrogen generator	integrated
Compressed air supply	7,000 hPa; 20 m³/h (102 psi; 706 ft³/h)
Dimensions (B x D x H)	
System	2,500 mm x 1,300 mm x 2,190 mm (98.4 x 51.2 x 86.2 in)
Recommended installation space	min. 4,800 mm x 3,600 mm x 2,900 mm (189 x 142 x 114 in)
Weight	approx. 1,250 kg (2,756 lb)
Data preparation	
Software	EOS RP Tools; EOSTATE; EOSPRINT; Materialise Magics RP with SG+ and further modules
CAD interface	STL. Optional: converter for all standard formats
Network	Ethernet

Form.1 Technical Data EOS M 290

2.2. EOS analysis tool box

In EOS M 290 machine, a comprehensive monitoring suite enables to conduct a real-time quality assurance of all production and quality relevant data. EOSTATE is composed of five different monitoring systems – System, Laser, PowderBed, MeltPool, and Exposure OT (optical tomography).

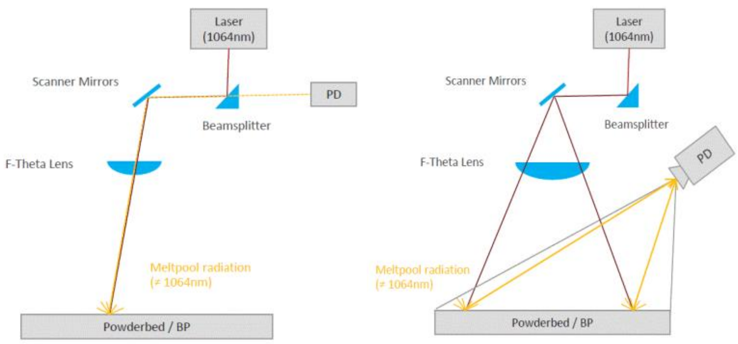


Fig.4 The position of on-axis diode and off-axis diode

There are two optical photodiodes on the machine. The one is on the laser beam axis to capture the reflected light data from the workpiece, which called the on-axis diode. The other one is settled on the beside of the workpiece as shown on figure 4. Due to its non-central position over the platform, the off-axis photodiode detects light form different position on the platform with different efficiency. If the off-axis need to be used, systematic error needs to be corrected first. For this project, the on-axis diode data was studied.

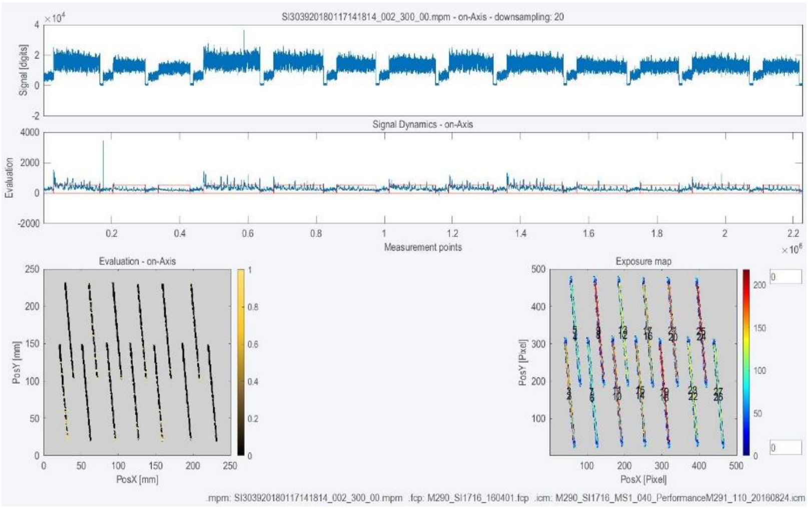


Fig.5 Main interface of the software

The figure shown above is the main interface of the tool box. The top window represents in this layer the light density changes with the time. Since the time also represents the sequence of sintering process, the x axis of the above window could represent the position of printing. The next window represents the evaluation of this layer with the specific algorithm. In this project, signal dynamics algorithm was selected. The red window was evaluated by the software depending the upper limit and the lower limit set by user. The lower-left window corresponds to the above information gotten from the evaluation. When the signal dynamics exceed the boundary of red window, the corresponding position of the layer will be marked the yellow pixel. For the other one that fulfill the restrict of red window, the corresponding position will be marked black pixel. The lower-right window is the exposure map as the visualization of datapoints.

For this project, we mainly focus on the evaluation window and the lower-left window.

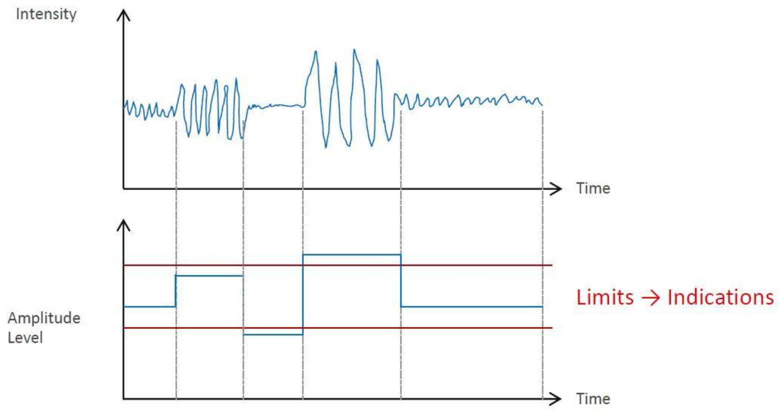


Fig.6 Schematic illustration of signal dynamics algorithm

The tool box provides three available algorithms for evaluation. People could choose one of them to evaluate the layer optical data or combine two or three to evaluate the data. For this project, we mainly focus on the signal dynamics algorithms. As shown on the figure 6, this algorithm wants to detect high dynamic process changes like splashy process and gas flow issues. The algorithm uses the FFT transform the intensity data to the frequency data. In this way, user could find the abnormal high frequency or low frequency time point which may finally affects the property of parts.

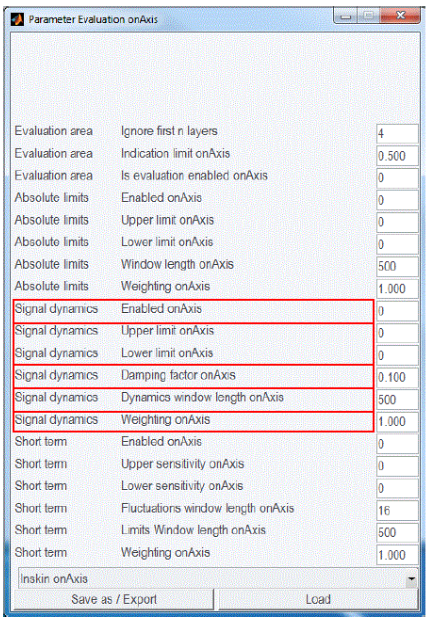


Fig.7 Setting parameters for signal dynamics algorithm

Setting parameter for the signal dynamic algorithm is very important for evaluation. The figure 7 with red window shows the key point for the setting. First red window is to enable the evaluation of signal dynamics. The second window I the upper and lower limit value setting which is the thresholds for the algorithm. Then is the damping factor which is the parameter affecting the core of the analysis algorithm, only change after consulting EOS. The forth window is the dynamics window length on axis which moves the average filtering length for signal dynamics calculation. The final one the weighing factor which only used for multiple algorithms. For this project, the setting parameter is shown below.

Signal dynamics

Upper limit	500
Lower limit	0
Damping factor	0.100
Dynamics window length	500
Weight	1.000

Form.2 Setting parameter for this project

3. Algorithms analysis

3.1 Case study

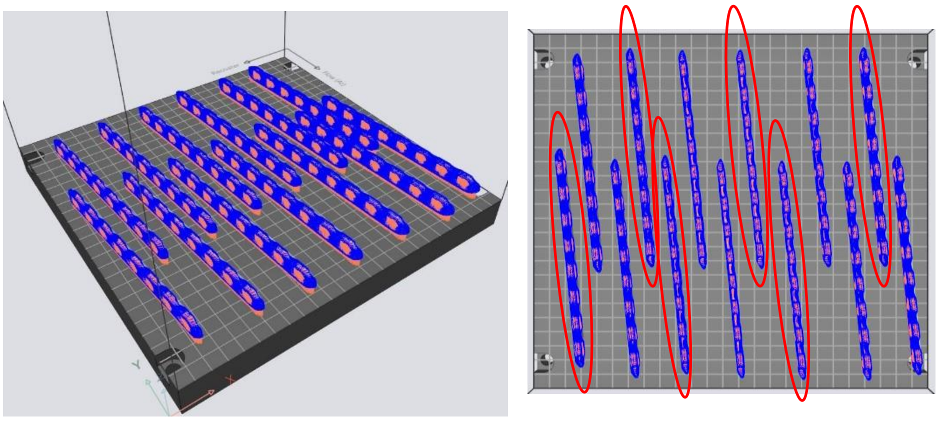


Fig.8 Case of 13 bars with holes inside

Due to the time limit, the research focus on the finished job from others. In this job, the EOS need to print 13 bars with 8 holes inside. For traditional machining process it’s a quite difficult work but for additive manufacturing, the print process is easy with little time consuming and less cost. Since the printer brush is hard, when there exists a huge defect the brush could not work again which enforce the user to cancel the part with huge defect. For this job, 5 of the bars were broken during the printing. The bar No 1, No 4, No 5, No 8, No 9 and No 12 were broken as shown in red circle in sequence of position.

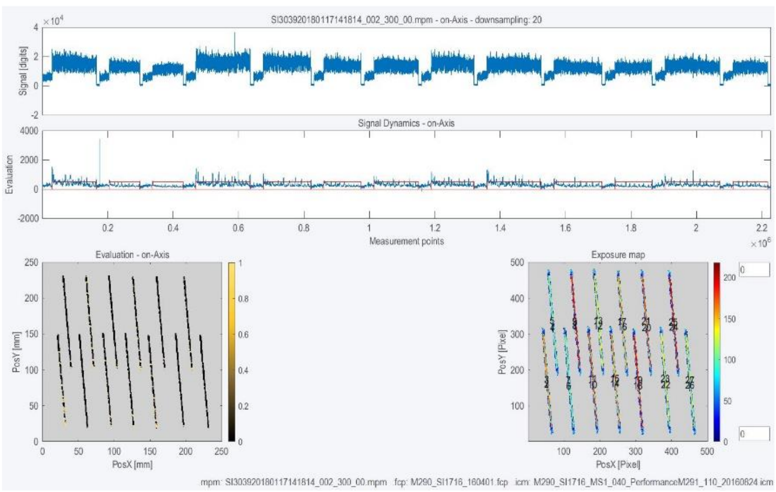


Fig.9 The evaluation of layer 115 with height 2300mm

This project wants to find some relationship between the printing failure and the diode collecting data. When focusing on the layer 115 as shown on figure 9 above, some difference appears. For the broken part, the signal dynamics have exceeded the red window quite a lot of times, which is much more than the normal parts. This tendency also shows on the lower-left window that the area of yellow pixels in broken part is larger than that in normal part.

Layer	Times of overshoot												
	1	2	3	4	5	6	7	8	9	10	11	12	13
2300mm	19	2	1	19	14	2	10	14	18	5	2	12	3
2320mm	16	0	0	18	8	2	10	5	16	5	0	11	2

Form.3 Eye counting the overshoot for each bar in layer 115 and 116

Since the previous tendency is just evaluate by the normal sense, for further research, the times of overshoot are counted by eye in layer 115 and layer 116. As shown in form 3, the red number represents the broken part and the others represents the normal part. It's obvious that for these two layers broken parts' signal dynamics exceeds the boundary more times than the others.

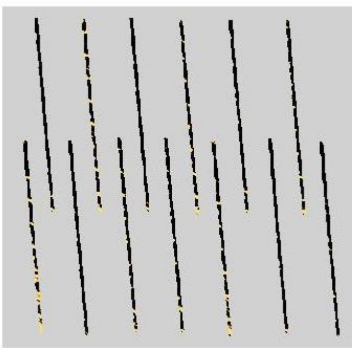


Fig.10 The lower-left window which represents the position that exceed the boundary

Since the counting by eye is not quite reliable, this project only takes it as the preliminary study. For further research, we need a more independent evaluation to compare the difference between the broken part and the normal part. To use the image processing algorithm to evaluate the difference, the lower-left window could be used as the research theme. If we could calculate the proportion of yellow region in whole bar, it could be considered as the evaluation algorithm.

3.2 Division algorithm

First, the research needs to divide each bar to the separable parts. There exists a lot of ways to solve this problem.

For solution 1, I learn it from the machine vision. We need to transform the RGB image to the grey level image. Then use the thresholds to separate the bars and the background and transform the grey level image to the binary image. And finally use the 'Bwconncomp' from the MATLAB tool box to separate the induvial bars from the background. However, there exists some problems in the thresholding process. When transform the RGB image to the grey level image with the 'rgb2grey' tool in MATLAB, the code calculates the grey level by the average value of R value, G value and B value. During this process, some information lost, and we could not separate the final parts from the back ground. Also, due to the defects and the broken parts in the evaluation, this algorithm could misunderstand the sequence of bars.

For solution 2, we could rotate the whole image first since the origin part has 5 degrees declination. After that, we could use the straight line to separate each part. But for this solution, the rotation could cause the defects in the matrix form. For the normal use, we could use interpolation to calculate the final value after rotation. But for this project, this way is unavailable since the research mainly focus on the pixel proportion. With the brightness interpolation, the final value will be affected seriously.

For solution 3, we must separate the parts by ourselves. It's quite time consuming and could only be used in this special case study. But it's suitable for this research. There are two divisions for this case. One is the square division and the slash division. As shown below, the square division solution uses the square to get the position of each bar and use the position to get the submatrix of the whole matrix. However, since the boundary of the bars changes with the time, the boundary may exceed the red window or affects the adjacent window which finally affects the accuracy of evaluation. Finally, the projects take the slash division to divide the parts.

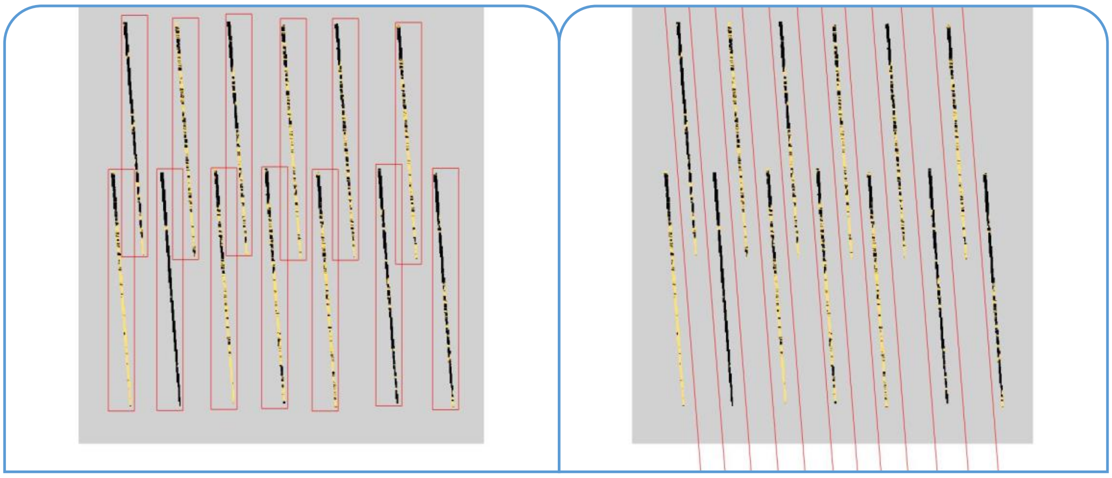


Fig.11 The square division and the slash division

4. Result analysis and conclusion

4.1 Trajectory of high frequency proportion for all layers

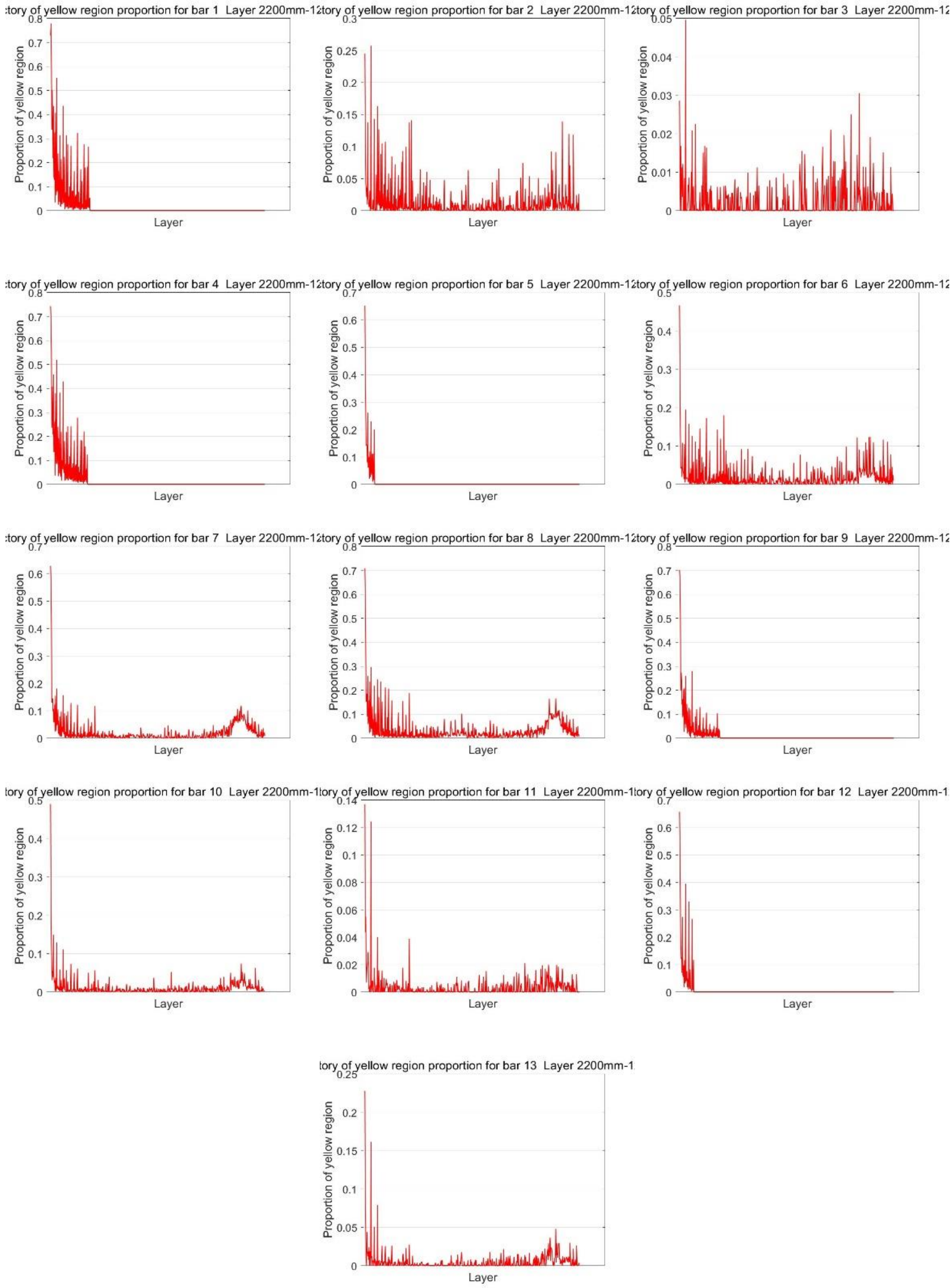


Fig.12 Trajectory of high frequency proportion for all layers in each bar

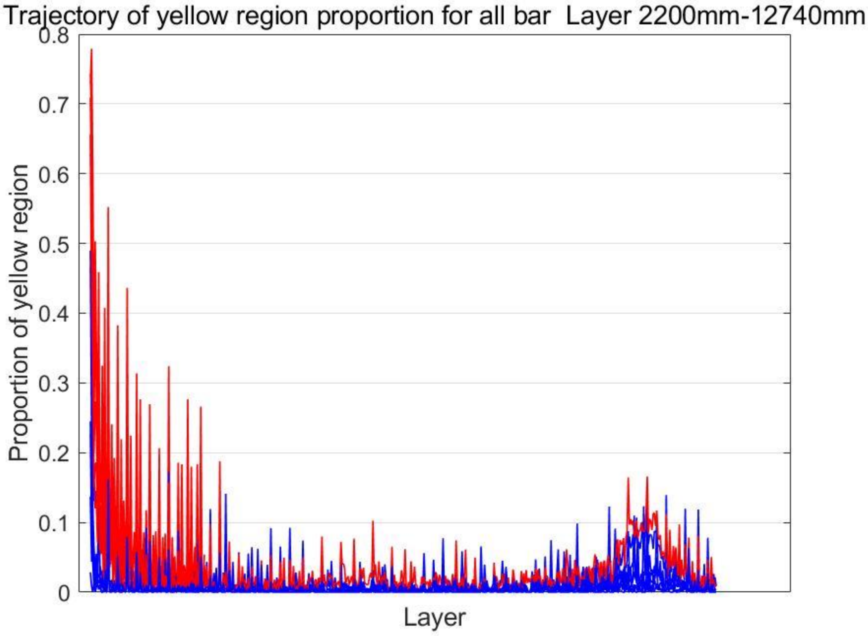


Fig.13 Trajectory of high frequency proportion for all layers

First, the project evaluates the yellow region proportion (high frequency proportion) trajectory during the printing process and combine them together in figure 13. In figure 13, the red lines represent 5 broken parts and blue lines represent normal lines. It could be found that for most of time, the red lines are above the blue line which means for most of time, the high frequency proportion in broken parts are higher than that in normal parts. What's more, the value is higher at the previous layers and lower at the latter layers.

4.2 Mean value of high frequency proportion in each bar

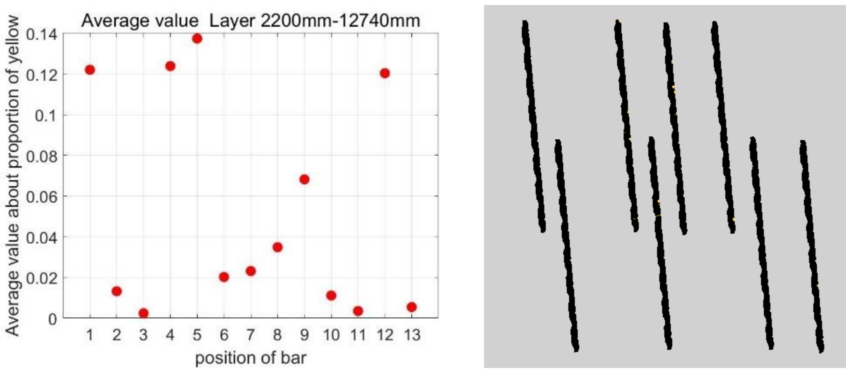


Fig.14 Mean value of high frequency proportion for case 1

Also, the research calculates the mean value for each bar in the whole printing process. The result is shown in figure 14. It could be found that for the broken part, the mean value of yellow proportion (high frequency proportion) is higher than that for normal part which corresponds to the trajectory results.

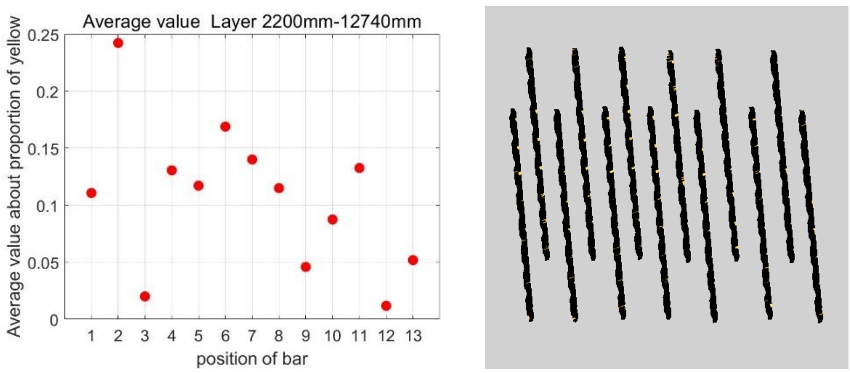


Fig.15 Mean value of high frequency proportion for case 2

The research also does the same evaluation for case 2 which is the same shape but different parameters as the case 1. For case 2, due to the fine design, all the bars are successful finally. There is no comparation in case 2.

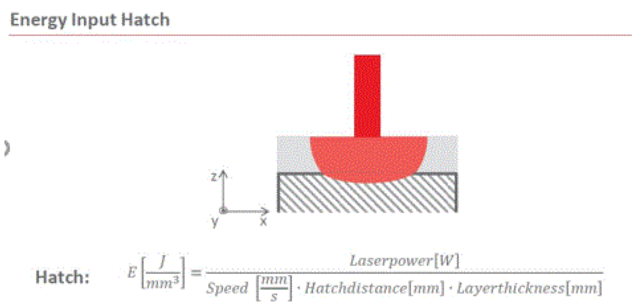


Fig.16 The calculation of energy input hatch

For the previous research, we could find that there exists a difference between the broken part and normal part. The tendency of this high frequency proportion is not quite clear. Due to the help of partner, the research focus on the laser energy for each bar. The calculation of energy input hatch could get from the parameter including the laser power, the scanning speed, the hatch distance and the layer thickness. The specific equation is shown in figure 16.

Real position from left to right	Laser Power	Scanning Speed	Hatch Distance	Energy input hatch		Proportion
3	195	1230	0.11	72.06		0.0024
13	195	1083	0.11	81.84		0.0055
2	234	1230	0.11	86.47		0.0132
11	195	1230	0.09	88.08		0.0035
7	195	866	0.11	102.35		0.0232
6	234	1230	0.09	105.69		0.0202
10	195	1230	0.07	113.24		0.0111
8	234	1083	0.09	120.04	Failed	0.0349
1	234	866	0.11	122.82	Failed	0.122
9	195	866	0.09	125.10	Failed	0.0682
12	195	1083	0.07	128.61	Failed	0.1204
5	234	1230	0.07	135.89	Failed	0.1374
4	234	866	0.09	150.12	Failed	0.1239

Form.4 The parameter and hatch power calculation in case 1

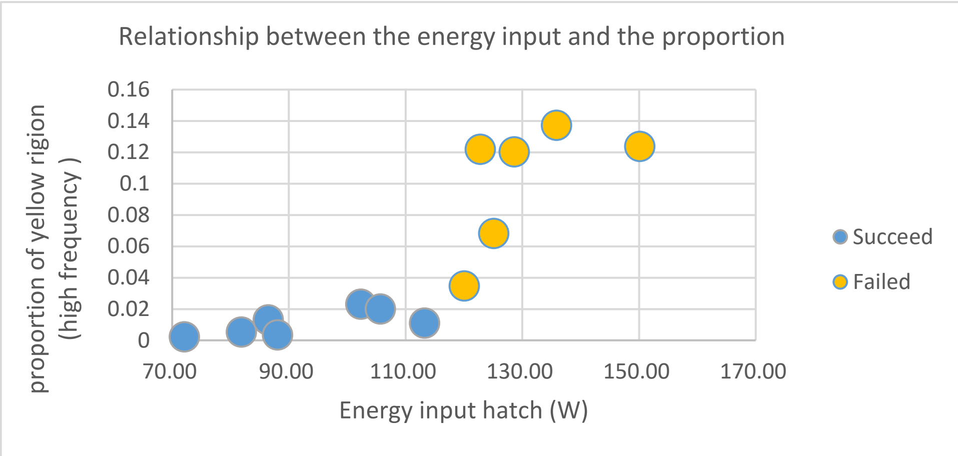


Fig.17 The relationship between the proportion and energy input hatch in case 1

With the rearrangement of energy input hatch, the result is shown in form 4 and figure 17. It’s obvious that there exists a tendency when the energy input hatch increase, and the proportion of high frequency also increase. And the figure also shows that there exists some threshold between the failed part and succeed part with the help of energy input hatch and the high frequency proportion.

Real position from left to right	Laser Power	Scanning Speed	Hatch Distance	Energy input hatch	Proportion
1	156	974	0.08	100.10	0.1107
2	215	1083	0.09	110.29	0.2423
3	146	1083	0.09	74.89	0.02
4	195	1083	0.09	100.03	0.1306
5	205	1137	0.09	100.17	0.1171
6	205	1083	0.08	118.31	0.1689
7	205	1029	0.1	99.61	0.1401
8	195	1137	0.08	107.19	0.115
9	156	1029	0.08	94.75	0.0459
10	195	1083	0.1	90.03	0.0875
11	195	1029	0.09	105.28	0.1327
12	156	1137	0.1	68.60	0.0118
13	156	1083	0.09	80.02	0.0519

Form.5 The parameter and hatch power calculation in case 2

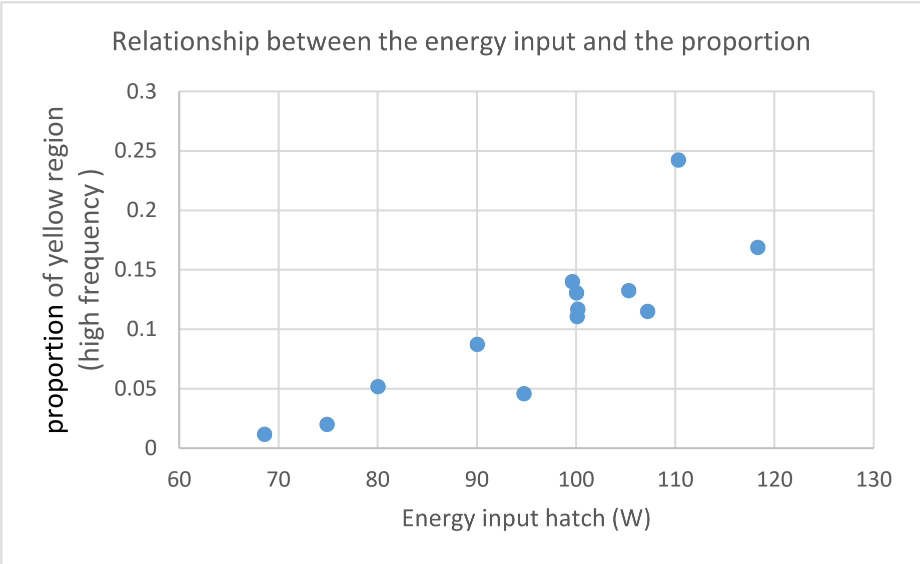


Fig.18 The relationship between the proportion and energy input hatch in case 2

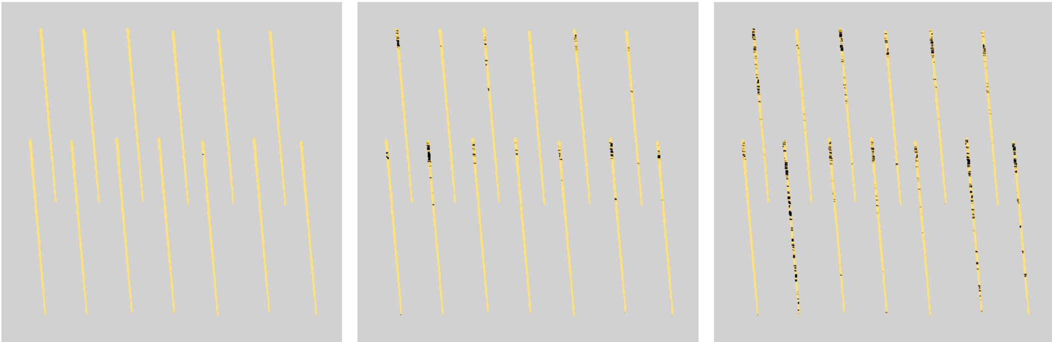
In case 2, the tendency when the energy input hatch increase, and the proportion of high frequency also increase also exists. The threshold of energy input hatch may be around 120W with the results shown in case 1 and case 2.

4.3 Result summary

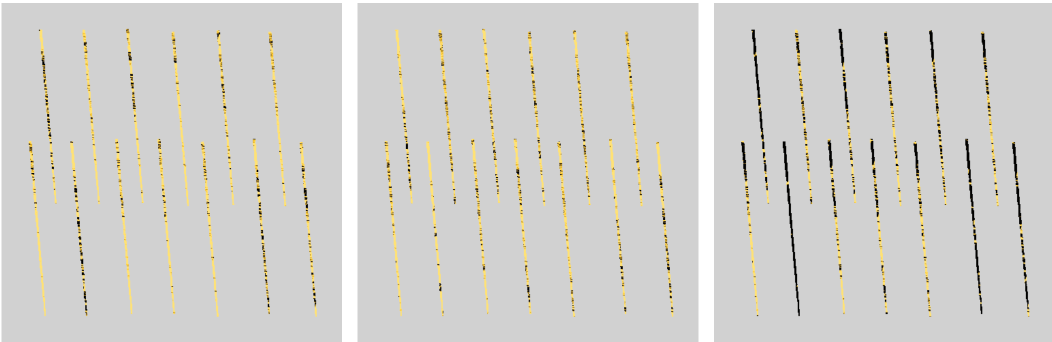
Laser beam energy may be the key point that affects the success of the printing job in this special case. There exists a relationship between the energy input hatch and proportion of high frequency. And could use the high frequency proportion to estimate the failure and even the properties of parts.

5. Extension and future work

5.1 Extension for frequency map combination



0Hz-100Hz   100Hz-200Hz   200Hz-300Hz



300Hz-400Hz   400Hz-500Hz   500Hz-

Fig.19 Each upper limit and lower limit for all range of layer 110

For extension research, I have done some exploration in the frequency combination map. Since the high frequency is just an indirect evaluation to the frequency evaluation. Since the row data is unavailable, a new idea that divided the value separately comes up. As shown on the figure 19, use all range of upper limits and lower limits to cover all range of frequency. In reverse, the black pixel is the position that fulfill the requirement in the boundary. Calculate the mean value of each range and sum it together and then get the approximation of frequency of each bar. Also, for each layer, find the pixel for each range and combine it together to get the frequency distribution. Both of these two directions are valueable.

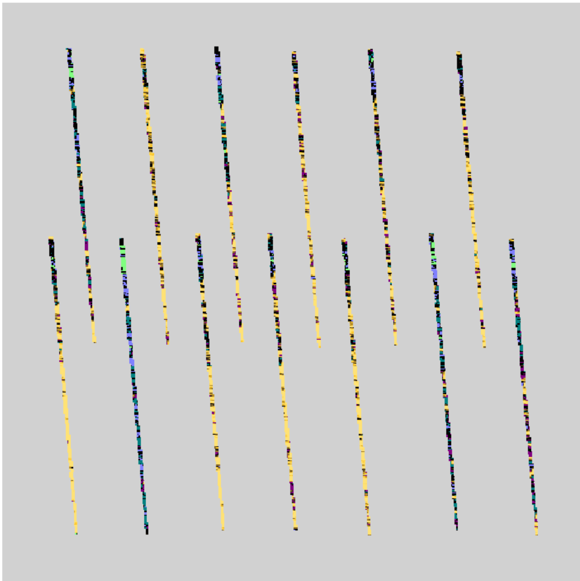


Fig.20 The combination of each frequency range in layer 110

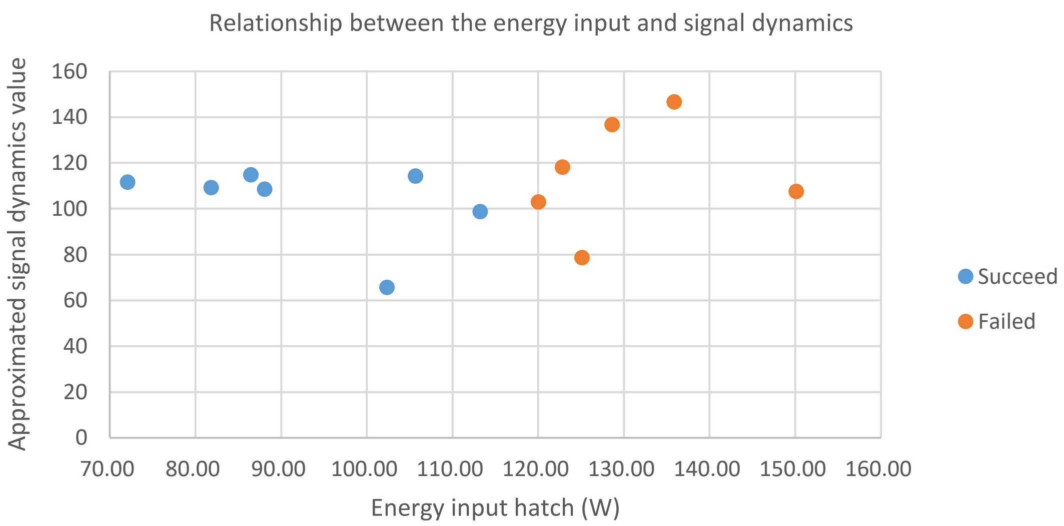


Fig.21 The relationship between the approximated frequency and energy input hatch in case 1

As shown on figure 20, the combination of layer 110 is failed due to the mistake from the pixel recognition, which also affects the approximation of frequency value. These two directions need more research on it.

5.2 Future work

Although the tendency could be found on in this case, there need more experiment to support the results. Due to the time limitation, this project only explores two similar cases. Also, the division solution only could be used on this special case. All of these problems need exploration.

Reference

[1]. Wilkes, J., Hagedorn, Y. C., Meiners, W., & Wissenbach, K. (2013).Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting. Rapid Prototyping Journal, 19(1), 51-57.
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[3]. Foster B, Reutzel E, Nassar A, et al. Optical, layerwise monitoring of powder bed fusion[C]//Solid Freeform Fabrication Symposium, Austin, TX, Aug. 2015: 10-12.
[4]. Coeck S, Bisht M, Plas J, et al. Prediction of lack of fusion porosity in selective laser melting based on melt pool monitoring data[J]. Additive Manufacturing, 2019, 25: 347-356.

Appendix 1 MATLAB code for the calculation

```
clear all; close all;
%%
%CACULATION
for k =2200:20:12740
k_1 = floor(k/10000);
k_2 = floor((k-k_1*10000)/1000);
k_3 = num2str(k-k_1*10000-k_2*1000,'%03d');
discription1 =
sprintf('part1_SI303920180117141814_0%d%d_%s_00.mpm_eval_onoffaxis.tif',k_1,k_2,k_3);
[X,map] = imread(discription1);
if ~isempty(map)
    I = ind2rgb(X,map);
end
black = zeros(528,13);
grey = zeros(528,13);
yellow = zeros(528,13);
    for i = 1:500
        for j = 1:500
            if ((j-39)/44-i/500)<0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,1) = black(k/20-109,1)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,1) = grey(k/20-109,1)+1;
                else
                    yellow(k/20-109,1) = yellow(k/20-109,1)+1;
                end
            elseif ((j-70)/44-i/500)<0&&((j-40)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,2) = black(k/20-109,2)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,2) = grey(k/20-109,2)+1;
                else
                    yellow(k/20-109,2) = yellow(k/20-109,2)+1;
                end
            elseif ((j-102)/44-i/500)<0&&((j-70)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,3) = black(k/20-109,3)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,3) = grey(k/20-109,3)+1;
                else
                    yellow(k/20-109,3) = yellow(k/20-109,3)+1;
                end
            elseif ((j-139)/44-i/500)<0&&((j-102)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,4) = black(k/20-109,4)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,4) = grey(k/20-109,4)+1;
                else
                    yellow(k/20-109,4) = yellow(k/20-109,4)+1;
                end
            elseif ((j-168)/44-i/500)<0&&((j-139)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,5) = black(k/20-109,5)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,5) = grey(k/20-109,5)+1;
                else
                    yellow(k/20-109,5) = yellow(k/20-109,5)+1;
                end
            elseif ((j-200)/44-i/500)<0&&((j-168)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,6) = black(k/20-109,6)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,6) = grey(k/20-109,6)+1;
                else
                    yellow(k/20-109,6) = yellow(k/20-109,6)+1;
                end
            elseif ((j-234)/44-i/500)<0&&((j-200)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,7) = black(k/20-109,7)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,7) = grey(k/20-109,7)+1;
                else
                    yellow(k/20-109,7) = yellow(k/20-109,7)+1;
                end
```

```
            elseif ((j-264)/44-i/500)<0&&((j-234)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,8) = black(k/20-109,8)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,8) = grey(k/20-109,8)+1;
                else
                    yellow(k/20-109,8) = yellow(k/20-109,8)+1;
                end
            elseif ((j-296)/44-i/500)<0&&((j-264)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,9) = black(k/20-109,9)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,9) = grey(k/20-109,9)+1;
                else
                    yellow(k/20-109,9) = yellow(k/20-109,9)+1;
                end
            elseif ((j-332)/44-i/500)<0&&((j-296)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,10) = black(k/20-109,10)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,10) = grey(k/20-109,10)+1;
                else
                    yellow(k/20-109,10) = yellow(k/20-109,10)+1;
                end
            elseif ((j-370)/44-i/500)<0&&((j-332)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,11) = black(k/20-109,11)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,11) = grey(k/20-109,11)+1;
                else
                    yellow(k/20-109,11) = yellow(k/20-109,11)+1;
                end
            elseif ((j-410)/44-i/500)<0&&((j-370)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,12) = black(k/20-109,12)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,12) = grey(k/20-109,12)+1;
                else
                    yellow(k/20-109,12) = yellow(k/20-109,12)+1;
                end
            elseif ((j-410)/44-i/500)>=0
                if I(i,j,1)<=0.2 && I(i,j,2)<=0.2 && I(i,j,3)<=0.2
                    black(k/20-109,13) = black(k/20-109,13)+1;
                elseif I(i,j,1)>=0.8 && I(i,j,2)>=0.8 && I(i,j,3)>=0.8
                    grey(k/20-109,13) = grey(k/20-109,13)+1;
                else
                    yellow(k/20-109,13) = yellow(k/20-109,13)+1;
                end
            end
        end
    end
%%
%OUPUT OF EACH LAYER
x = 1:13;
for n = 1:13
proportion(k/20-109,n) = yellow(k/20-109,n)/(black(k/20-109,n)+yellow(k/20-109,n));
end
plot(x,proportion(k/20-109,:),'r.','markersize',30);
hold on;
grid on;
set(gca,'xtick',x);
xlabel(gca,'position of bar','FontSize',16);
ylabel(gca,'proportion of yellow','FontSize',16);
set(gca,'FontSize',14)
discription2 = sprintf('Proportion of yellow in each bar  Layer %dmm',k);
title(discription2,'FontSize',16);
discription3 = sprintf('Layer %dmm.jpg',k);
saveas(gcf,discription3);
close;
end
```

Appendix 2 MATLAB code for the evaluation

```
clear all; close all;
%%
%LOAD
load('result.mat');
%% OUPUT OF AVERAGE VALUE
proportion=proportion(~isnan(proportion));
id = isnan(proportion);
proportion(id) = 0;
proportion_mean = sum(proportion)./sum(~id);

proportion_mean = mean(proportion,'omitnan');
proportion_mean_test = mean(proportion(1:97,1));

plot(x,proportion_mean,'r.','markersize',30);
hold on;
grid on;
set(gca,'xtick',x);
xlabel(gca,'position of bar','FontSize',16);
ylabel(gca,'Average value about proportion of yellow','FontSize',16);
set(gca,'FontSize',14)
discription2 = sprintf('Average value  Layer 2200mm-12740mm');
title(discription2,'FontSize',16);
discription3 = sprintf('Layer 2200mm-12740mm average.jpg');
saveas(gcf,discription3);
%% OUTPUT OF TRAJECTORY
proportion(isnan(proportion)) = 0;
for i=1:13
k = 2200:20:12740;
plot(k,proportion(:,i),'r-','LineWidth',1);
hold on;
grid on;
set(gca,'xtick',x);
xlabel(gca,'Layer','FontSize',16);
ylabel(gca,'Proportion of yellow region','FontSize',16);
set(gca,'FontSize',14)
discription2 = sprintf('Trajectory of yellow region proportion for bar %d  Layer 
2200mm-12740mm',i);
title(discription2,'FontSize',16);
discription3 = sprintf('Trajectory of %d.jpg',i);
saveas(gcf,discription3);
hold off;
close;
end

%% OUTPUT OF TRAJECTORY FOR ALL BARS
k = 2200:20:12740;
plot(k,proportion(:,1),'r-','LineWidth',1);
hold on;
plot(k,proportion(:,2),'b-','LineWidth',1);
plot(k,proportion(:,3),'b-','LineWidth',1);
plot(k,proportion(:,4),'r-','LineWidth',1);
plot(k,proportion(:,5),'r-','LineWidth',1);
plot(k,proportion(:,6),'b-','LineWidth',1);
plot(k,proportion(:,7),'b-','LineWidth',1);
plot(k,proportion(:,8),'r-','LineWidth',1);
plot(k,proportion(:,9),'r-','LineWidth',1);
plot(k,proportion(:,10),'b-','LineWidth',1);
plot(k,proportion(:,11),'b-','LineWidth',1);
plot(k,proportion(:,12),'r-','LineWidth',1);
plot(k,proportion(:,13),'b-','LineWidth',1);
grid on;
set(gca,'xtick',x);
xlabel(gca,'Layer','FontSize',16);
ylabel(gca,'Proportion of yellow region','FontSize',16);
set(gca,'FontSize',14)
discription2 = sprintf('Trajectory of yellow region proportion for all bar  Layer 
2200mm-12740mm');
title(discription2,'FontSize',16);
discription3 = sprintf('Trajectory for all bars.jpg');
saveas(gcf,discription3);
```

Appendix 3 MATLAB code for extension (the combination of frequency map)

```
clear all; close all;
%%
%LOAD
load('result_0_100.mat');
load('result_100_200.mat');
load('result_200_300.mat');
load('result_300_400.mat');
load('result_400_500.mat');
load('result_500_600.mat');
%% OUPUT OF AVERAGE VALUE
proportion_mean_0_100 = mean(proportion_0_100,'omitnan');
proportion_mean_100_200 = mean(proportion_100_200,'omitnan');
proportion_mean_200_300 = mean(proportion_200_300,'omitnan');
proportion_mean_300_400 = mean(proportion_300_400,'omitnan');
proportion_mean_400_500 = mean(proportion_400_500,'omitnan');
proportion_mean_500_600 = mean(proportion_500_600,'omitnan');
for i = 1:13
   proportion_signal_dynamic(i) =
50*proportion_mean_0_100(i)+150*proportion_mean_100_200(i)+250*proportion_mean_200_300
(i)+350*proportion_mean_300_400(i)+450*proportion_mean_400_500(i)+550*proportion_mean_
500_600(i);
end
```