Laser Based Manufacturing

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Module # 06

Lecture # 21

Process and Performance Parameters of Laser-Based Additive Manufacturing Techniques

Hello everyone. I welcome you all to the last lecture. We are at laser based additive manufacturing techniques and this week we have already studied the fundamentals of additive manufacturing as well as the stereolithography process.

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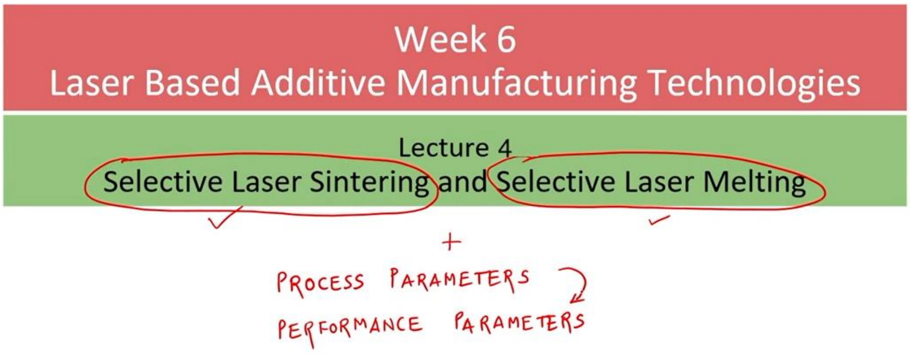

In this lecture we will be studying the process parameters involved in laser based additive manufacturing and their influences - laser parameters, performance parameters and the influence of process parameters on performance parameters. Now let us see what are the various process parameters which are important in this SLS and the stereolithography process.

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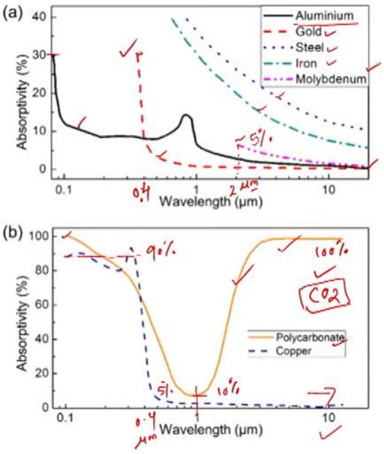

Figure. Light absorptivity at different wavelengths of (a) Various metals; (b) Polycarbonate and copper

Operating Wavelength

- Most important parameter : different materials interact with different wavelengths
- A high material absorption at applied laser wavelength is desirable since the target material should efficiently interact with the incident laser light
- High absorptivity leads to higher productivity
  - For metal powders, shorter wavelength better the light absorptivity
  - **Nd:YAG or Yb-fiber lasers with 1064 nm** operating wavelength exhibit a higher throughput than CO_2 laser with 10.6 micrometer operating wavelength
  - For polymeric materials, absorptivity is much higher at 10.6 micrometer than 1064 nm -> **high usage of CO_2 laser with polymers**
- Operating wavelength is also related to focusability, which determines ultimate manufacturing resolution.
- Minimum focussed spot size is proportional to wavelength due to optical diffraction limit -> CO_2 lasers not suitable for micro/nano-scale manufacturing

Lee, Hyub & Lim, Chin Huat Joel & Low, Mun Ji & Tham, Nicholas & Vadakke Matham, Murukeshan & Kim, Young-Jin. (2017). Lasers in additive manufacturing: A review. International Journal of Precision Engineering and Manufacturing-Green Technology. 4. 307-322. 10.1007/s40684-017-0037-7. 13

The primary process parameter is the operating wavelength. There are various materials that we have seen and they are interacting with the lasers at different wavelengths. As the material is getting changed, we have to change the wavelength or we have to choose the laser with that sort of wavelength. It is expected that there should be very high energy absorption during the laser material interaction. High energy absorption at applied laser wavelength is desirable since the target material should efficiently interact with the incident laser light, therefore the wavelength has to be chosen very carefully. When there is a high absorptivity, that is certainly leading to high productivity because there would be more melting, efficient melting, and then we can have the required operation done. It may be the metal melting or the polymer sintering. For metal powders, shorter the wavelength, better the absorptivity, that is the obvious thing. If there is a shorter wavelength that we are applying, the metals will absorb the laser energy at a higher stake and then we can generate the required work done.

In general, the Nd:YAG lasers or YB-fiber lasers with a wavelength of about 1064 nanometer, they are exhibiting a higher throughput in comparison with the CO_2 laser. CO_2 gas laser, its wavelength is very high, it is about 10.6 micrometer, it is quite high. And such CO_2 lasers are not that useful for the operations when we want to process the materials with very shorter wavelengths. For metal powders, for SLM, basically Nd:YAG lasers would be of a good choice. For polymeric materials the absorptivity is much higher at 10.6 micrometer than the 1 micrometer that is 1064 nanometer. Therefore the CO_2 lasers are widely being used, they are popular, they are useful when we are processing the polymers.

On your screen you can see the variation of absorptivity in percentage with respect to the the wavelength for variety of materials. This is the graph that you can see over here. The black line is with respect to the aluminum, and you can see the maximum absorptivity is about 30 percentage and that is for very short wavelength less than 0.1 micron. And as we increase the wavelength, the absorptivity is getting reduced and it reaches 0% when we go for very high wavelength, more than 10 micron. For other materials such as gold, steel, iron and molybdenum, the curves are there in front of you. Based upon these curves, you can choose the laser for the particular operation. Here you just notice the absorptivity, for gold it is starting from about 30 percentage and it is for about 0.4 micron wavelength, it is showing very good absorptivity 30% but as you increase the wavelength the absorptivity is getting reduced.

For molybdenum, you just notice here the absorptivity is starting at the value of about. 5 percentage for 2 micron and it is getting reduced further. For polycarbonates, its very interesting, you can notice that the absorptivity is very high for very shorter wavelength. about 0.1 micron and when we increase the wavelength the absorptivity is getting reduced, for 1 micron it is almost about 10 percentage - very low and as we increase the wavelength, the absorptivity is reaching again to the 100 percentage. This is the domain of the CO_2 lasers where we can process the polycarbonates.

For copper material the absorptivity is approximately about 90 percentage till 0.4 micrometer wavelength and then suddenly it is dropping to about 5 percentage. And then there is a sharp decrease in the absorptivity to five percentage from 90 percentage when we increase the wavelength from 0.4 micron to 0.5 micron, further it is reducing and reaching to about zero percentage or no absorptivity for wavelength about 10 microns.

The operating wavelength is also related to focus ability, which determines the ultimate manufacturing resolution. There are two aspects in the wavelength: if we reduce the wavelength and if we reduce the diameter of operation. The operating wavelength is related to the focus ability and the focus ability is also controlling the manufacturing resolution. If we are not able to focus less than 10 microns then we cannot manufacture the components below 10 micron size. Focusing of the laser is very much important in the manufacture of micro-sized or nano-sized components. The minimum focused spot size is proportional to the wavelength due to the optical diffraction limit. As we are increasing the wavelength, the minimum focused spot size is also getting increased. Here I can write, the wavelength is directly proportional or it is controlling the minimum focused spot size. That means for micro manufacturing or for micro features or products, we need to go for low value of wavelength. The Nd:YAG lasers or the lasers which are giving or which are working below say 0.1 micron, that is also good for generation of micro features. And certainly, the CO_2 lasers which is having the wavelength of about 10 microns i.e., 10.6 microns that is for the CO_2 laser and these CO_2 lasers are not suitable for micro manufacturing.

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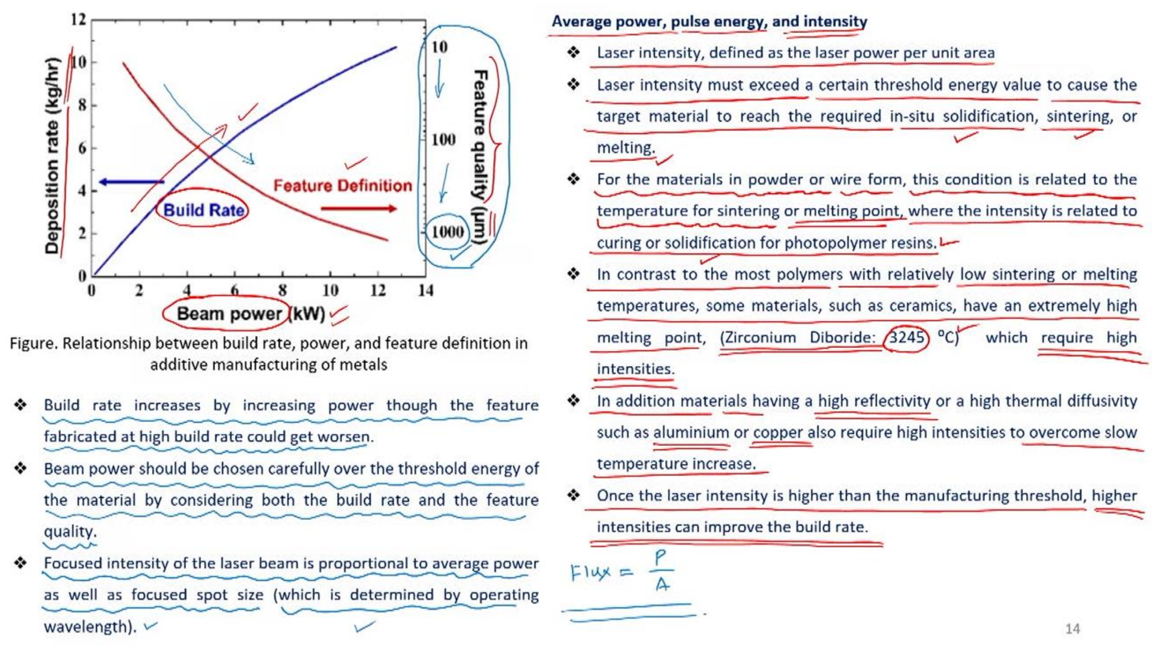

The next parameter is beam power and how the beam power is playing the role in the laser based additive manufacturing techniques. There are two parameters, two performance parameters here we are studying that is: the build rate or you can say it is a deposition rate and the deposition rate is in kilogram per hour. The beam power here we are considering in kW. In the same graph we have also plotted the feature quality that is in microns.

Let us see what is the effect of beam power on the deposition rate or build rate and the feature definition. The beam power is deciding the pulse energy and the intensity as well. If you keep the diameter constant, the power is also controlling the density. The laser intensity is defined as the laser power per unit area. Laser intensity must exceed a certain threshold energy value to cause the target material to reach the required in situ solidification or sintering or melting. We have to generate the laser intensity in such a way that it should generate the required solidification in case of polycarbonates and sintering or melting in case of the SLS based process or/and the SLM based process.

For the materials in powder or wire form, this condition is related to the temperature for sintering or the melting point where the intensity is related to the curing or solidification in photopolymer-based resins. When we are carrying out photopolymerization of the resins, the intensity should produce the required solidification and when we are working for sintering or melting then the intensity should melt or generate the required temperature to carry out the required operation.

In contrast to the most of the polymers with relatively low sintering or melting temperature, some materials such as ceramics have an extremely high melting point. Zirconium diboride in particular the ceramics such as zirconium diboride, it is having an extremely high melting point - it is 3245°C, which requires high intensities. When we want to process the ceramics type of materials, we have to apply more and more power to melt the granules or the the tiny bits of these materials. In addition, not only the materials which are having high melting point, there are certain materials which are having high reflectivity. To process such materials we have to cross the threshold of the absorption. In this case as well when we want to process high reflective materials such as the aluminum and copper, we have to apply more and more intensities to get the required work done to overcome the slow temperature increase. Once the laser intensity is higher than the manufacturing threshold, higher intensities can improve the build rate. To improve the build rate, we have to apply the high laser intensity to get our work done.

Now on your screen you just observe the curves, we do have two curves that is the blue curve. The blue curve is designating the variation of deposition rate or build rate with respect to the beam power. You can clearly notice here that as we increase the beam power, there is increase in the build rate. However, in case of feature definition, as we increase the laser power from, say 1 kilowatt to 12 kilowatt, the size of the feature is getting increased. Here you can notice, from 10 microns to 1000 microns - more the power that we are applying, more or the broader or the bigger features we can create. The build rate is increasing by increasing power though the feature fabricated at high build rate could get worsened. In this case the quality of the feature is getting deteriorated because we are only able to manufacture a broader feature when the high power is applied. Here even we are not able to maintain the quality of the features, we cannot able to maintain the corners or the edges when we apply more and more power. The feature quality is not only with the dimension, it is with respect to the corners that we are getting, the edges that we are getting, the curve, the accurate curve that we are getting during this operation. Here the feature quality is not only with respect to the dimension of the deposition, it is with respect to the area that that is getting deposited. When larger power is being applied, the feature quality or the control over the accuracies or the complexities of the feature would get lost because we are getting the feature size in thousands of microns.

Consider a very small product and that to be manufactured or that to be deposited by the AM, the laser-based AM of 50 microns and if we are applying 10 kilowatt in that case the deposition would be of higher side say 500 microns or 1000 microns and naturally, we will not able to achieve its required feature quality - so that has to be taken into consideration. When we are applying higher laser the quality is getting worsen, the feature is getting worsen, the amount of deposition is very high, and that has been noticed over here. As we increase the beam power, the feature sizes are getting increased, the deposition is getting increased but as far as the feature quality is concerned it is getting reduced. Therefore, the beam power should be chosen carefully over the threshold energy of the material by considering both build rate as well as the feature quality. I would like to emphasize again, and this is not with respect to the quality, this is with respect to, you can consider as the size over here.

Focused intensity of the laser beam is proportional to average power as well as focused spot size, which is determined by the operating wavelength. The focused intensity of the laser beam, here I would like to mention is proportional to the average power size and the focused spot size, and that we have seen already: the intensity or the flux is power divided by area. This we have already seen, again it is noted over here.

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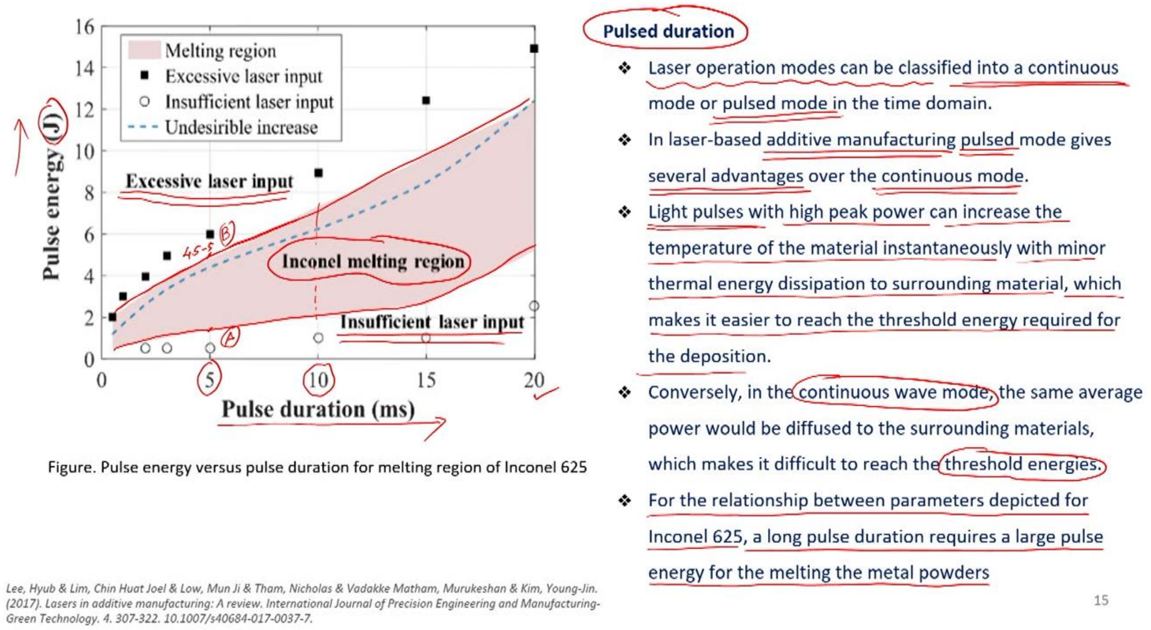

Now next parameter is pulse duration. On your screen you can see pulse duration we have taken on X-axis and it is varying from 0 ms to 20 ms and on and on Y-axis there is a variation of pulse energy. Laser operations can be classified into continuous or the pulse mode, which we have already seen. Either you can apply the laser in a continuous mode without having any pulses of the laser application or we can apply the energy in a discrete manner in pulse mode. As far as the additive manufacturing things are concerned, it is noted that the pulse mode is giving us very good advantages over the continuous mode. Light pulses with high peak power can increase the temperature of the material instantaneously with minor thermal energy dissipation to surrounding material which makes it easier to reach the threshold energy required for the deposition. This is very good concept actually and it is very important as well, when we are applying the light pulses of high peak power, there the energy dissipation to the surrounding material is minimal and the local temperatures would be very high. If you are applying the pulses consecutively, then locally the temperature would be increased without harming the surrounding material, without having significant HAZ. This is a very good characteristics of applying the pulse mode of energy deposition. This is leading to local temperature enhancement without affecting the surrounding material and that is saving the product, that we can have a much better product, we can reduce the thermal stresses generated during the AM manufacturing.

Conversely, in the continuous wave mode, the same average power would be diffused to the surrounding materials, which makes it difficult to reach the threshold energy. If we go for the continuous wave mode, we are continuously applying the laser power and this continuous application of the laser power facilitates the dissipation of energy which is getting entered inside the work piece, in the surrounding medium/surrounding region of that work part, and thus it is difficult to achieve the threshold energies and when there is no threshold energy is achieved, we cannot have the probable deposition, probable melting or the sintering operation being done.

For the relationship between parameters depicted for Inconel 625, a long pulse duration requires a large pulse energy for the melting the melt powders. For Inconel, it is a high strength material we have to go for pulses with high peak energy power. Here you can see there is a graph which I have noticed and this graph is giving us the regions and these regions are helping us to find out the region of insufficient laser input and the regions of excessive laser input as well. This is the Inconel melting region. One certain example I have taken over here. Here, the region has been noticed by varying the pulse duration on X-axis and pulse energy on the Y-axis. Suppose you are taking the pulse duration of 5 ms, certainly you have to generate the pulse energy between these two values. This value A and this Value B and the value B is about 4, 4.5 to 5 Joules. To get 4.5 or 5 joules, that much of power that you have to choose, that sort of laser that you should have, which will generate the 5 Joule of the pulse energy for the melting.

If suppose you are trying to work with longer pulse duration, for a longer pulse duration again, this particular line will help you to choose the appropriate laser powers by use of the pulse energy. From this graph you can compute the laser power or you can find out the required power that to be applied to get the melting done for processing of the Inconel.

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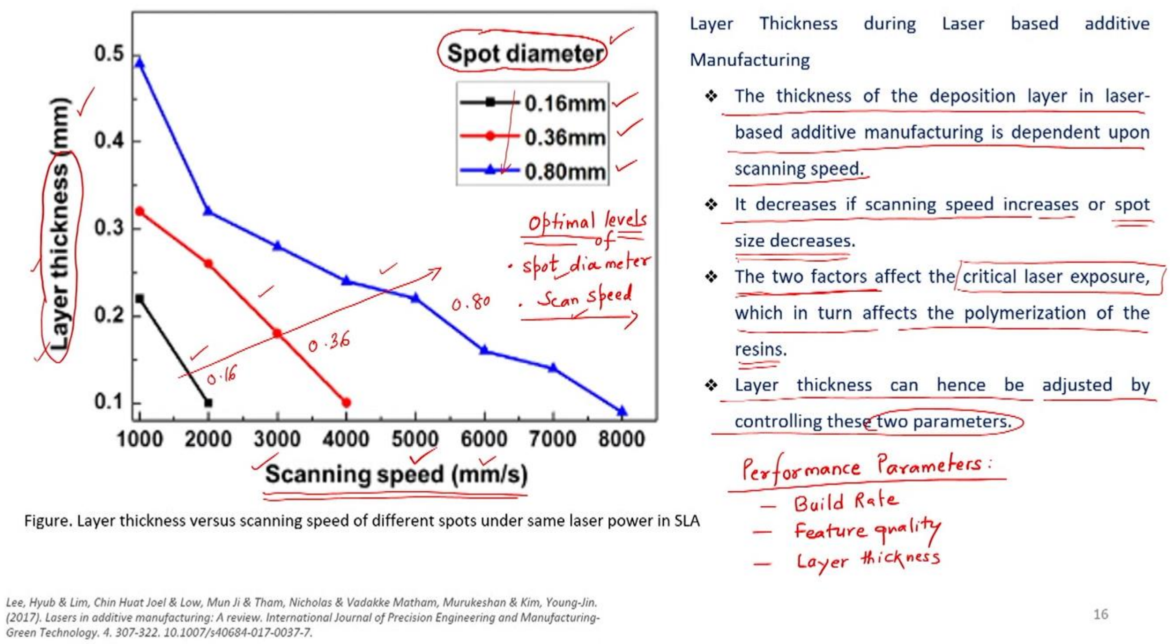

The next parameter is a spot diameter, we will see how the spot diameter is influencing the layer thickness. The layer thickness is a performance parameter. We have seen the performance parameters as per as AM. Here we are having build rate, feature quality and layer thickness.

Now let us study how the layer thickness is varying for spot diameter and we are also considering the scan speed as well. The scan speed is given in terms of mm/s. What we can notice over here, as we are increasing the scan speed, there is reduction in the layer thickness for all the spot diameters. If you consider the 0.16 mm of spot diameter, the layer thickness is reducing with scan speed increase. Same trend is for 0.36 mm of the spot diameter as well as 0.80 mm of the spot diameter. The thickness of the deposition layer in the laser based additive manufacturing is dependent upon the scan speed. The thickness of the deposition layer is decreasing if the scan speed is increasing or spot size is decreasing, which is very obvious. You just notice that as we are increasing the spot diameter, here you notice we are increasing the spot diameter the layer thickness is also increasing. This is for 0.16, this is 0.36 and this is for 0.80. As we are increasing the spot diameter the thickness is also getting increased. These two factors which factors? The speed and the spot diameter; they are affecting the critical laser exposure, which in turn affects the polymerization of the resins. The speed that is the interaction time, it decides and the area of the interaction that is decided by the spot diameter. Both these parameters are critically affecting the laser exposure and based on that we are getting the different layer thickness for variety of its combination. Layer thickness can hence be adjusted by controlling these two parameters. If you are controlling or if we are applying the optimal levels of scan speed and spot diameter, we have to find out the optimal levels of spot diameter and can speed. Then we can easily achieve the required layer thickness. The problem is very interesting, find out the spot diameter and scan speed for required layer thickness. For this purpose you have to carry out lot of experiments, you have to plan them systematically, execute the experiments systematically and then you can easily find out these optimal levels.

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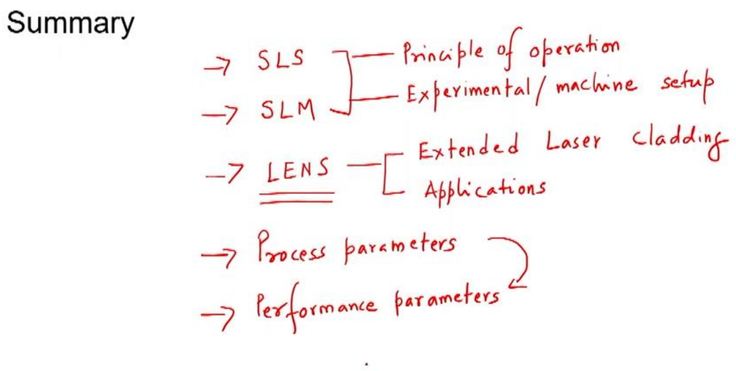

Well, with this I would like to conclude the today's lecture. It was quite comprehensive lecture. We have seen SLS (Selective laser sintering), then we have also seen the SLM (selective laser melting), the principle of operation of these two processes, then experimental setup or the machine setup that also we have seen: Experimental or the machine setup of SLM and SLS. Then we have also seen the LENS (laser engineered near net shape generation), that is LENS very useful technique which is nothing but the extended laser cladding process and we have also seen their applications. Then we have also seen various process parameters used in additive manufacturing. We have also studied the performance parameters such as build rate, feature quality and the layer thickness and the effect of process parameters on the performance parameters.

With this I would like to stop for this week as well in the next week we will see some of the mechanization or the automation related aspects by using lasers. We will also see what are the various, the CAD and CAM related aspects of the laser-based processing. Till now we have discussed or we have seen that there is a huge contribution of computer design and computer aided manufacturing, CNC technology as well to carry out all the operations. Till now we have seen such as the material removal or welding or the additive manufacturing, or even forming as well. Everywhere there is a contribution of the CNC technology. Let us look at some of the aspects in our next week that is the week number 7. Till then goodbye. Thank you.