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Scanning optics enabled possibilities and challenges in laser cladding

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Abstract

Laser cladding using a scanned beam is quite a similar process than laser cladding using static optics (e.g. lens or mirror optics). The main difference comes from the manipulation of the laser beam. In laser cladding with scanning optics the laser beam is manipulated with a scanner so that the laser's area of influence can be shaped numerically. This increases cladding process flexibility. Scanning optics enable laser beam modification considerably versatile way than normal static optics can. This is due to possibility of numerical adjustment of scanning amplitude, laser power and scanning frequency. By modifying these parameters clad beads geometry can by modified quite freely. However scanned laser beam in surface modification process creates some restricting factors to the process. Mainly limitations for the process parameter values come from the dual characteristics of the energy input. This paper treats usability of scanning optics in laser cladding process in general level. In this paper is discussed how scanned beam can be used to increase the flexibility but also maters that limit the usage of scanned beam in cladding process. Process possibilities and limitations are presented in trough experimental data and examples.
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Keywords: Linear scanner; Energy input; Process stability; Dilution; Power modulation

1. Introduction

Scanner optics is one viable way to control and shape a high power laser beam for cladding purposes. In fact, a scanner technique has been used as early as the late 1970's by Belmont and Castagna (1979) and early 1980's by in

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laser cladding studies and even in production in order to modify the laser beam interaction zone to the desired form. However, there is very little information on how a scanned beam changes the process dynamics of the cladding process. Most studies [e.g. Belmont and Castagna (1979), Bruck (1987), Klocke et al. (2010), Klockea et al. (2012), Turichin et a. (2012), Tuominen et al. (2011)] where laser cladding has been done using scanning optics, scanner optics have mainly been only as a tool for modifying the laser interaction area to a desired size and shape. In these studies, there has been very little consideration as to how a scanned beam affects the cladding process itself.

1.1. Process parameters

Laser cladding process parameters can be divided in two categories; energy input side and energy consumptive side, figure 1 and equation 1 and 2. In order for the process be successful there must be balance between the energy input side and the using Too high an imbalance towards either side can cause imperfections to the clad bead quality, e.g. too high dilution or lack of fusion side. Bruck (1987), Weerasinghe and Steen (1987), Partes et al. (2004), Pinkerton and Li. (2004), Kaplan and Groboth (2001), Pelletier et al. (1993)

$$Q_{si} = P/D_f\, v \tag{1}$$
$$Q_{su} = p_{fa} c_p \Delta T + p_{fa} L \tag{2}$$

Where Q_s is specific energy input (J/mm2), P is laser power (W), D_f is laser spots diameter (mm) and v is cladding speed. Q_{su} is specific energy usage that is needed for melting all the powder material per square millimeter (J/mms), p_{fa} powder material fed per square millimeter (g/mm2), c_p powder materials heat capacity, ΔT material temperature rise from initial temperature to melting temperature (°K) and L specific latent heat for melting (J/g).

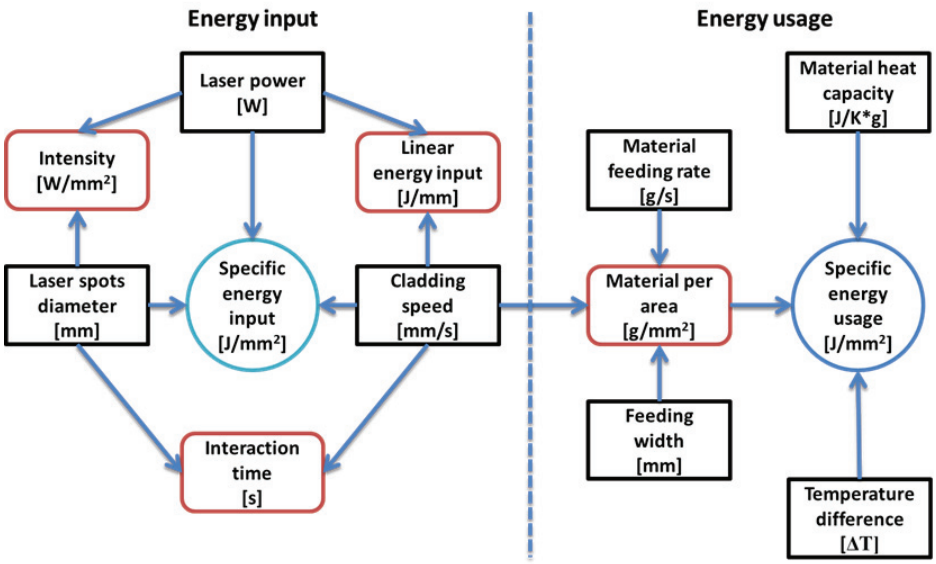

Fig. 1. Laser cladding process parameters and their relationship to each other.

As the laser power determines how much energy there is, laser spot diameter defines how large are this energy is divided, figure 1. Ion 2005 and Toyserkani et al. 2004 stated in their books that an intensity of around 100 W/mm2 is appropriate for laser cladding. Much higher intensities can expose the cladding process to vaporization and much lower intensities do not create melt pool. Intensity is quite typical case of laser cladding parameters, it is defined by two primary parameter and in order to process to work properly it should be in certain range. The powder feed rate pfr (g/s) ultimately defines how much additive material there is to be melted by the laser beam per time unit. The powder feed rate unambiguously defines the minimum energy that is needed to melt all the additive material and thus

it defines the minimum laser power needed. The effect of cladding speed v (mm/s) on the cladding process is multifaceted. This is because the cladding speed affects both the energy input and usage sides, figure 1, and thus it is a binding factor between these two sides. Cladding speed defines how long time laser beam imports energy to a specific location, Q_{si} (J/mm2), but also how long time the powder feeding is in interaction with this same specific point Q_{su} (J/mm2). As cladding parameters are related to each other, it must be understood that when one parameter is adjusted this can affect many other factors. This is why the cladding process is more than the sum of its parameters and must be treated and adjusted as a whole. Pinkerton and Li. (2004), Pelletier et al. (1993), Picasso et al. (1994), Han et al. (2004)

Powder feeding creates a powder cloud on top of the melt pool, which absorbs energy from the laser beam and causes an attenuation effect. Powder feeding angles affect both the rise in temperature of the powder particles and the laser power attenuation, this effect comes from the geometry, figure 2. Powder feeding angle θ defines how long inside the laser beam the powder particles go, x' in figure 2. As the θ approaches 90 º the powder cloud's height in relation to the laser beam increases. As the powder cloud's height in relation to the laser beam increases the probability of photons interacting with powder particles will increase and thus attenuation increases. Pelletier et al. (1993), Picasso et al. (1994), Neto and Vilar (1998), Huang et al. (2005), Li et al. (1996), Lin (2000), Fu et al. (2002)

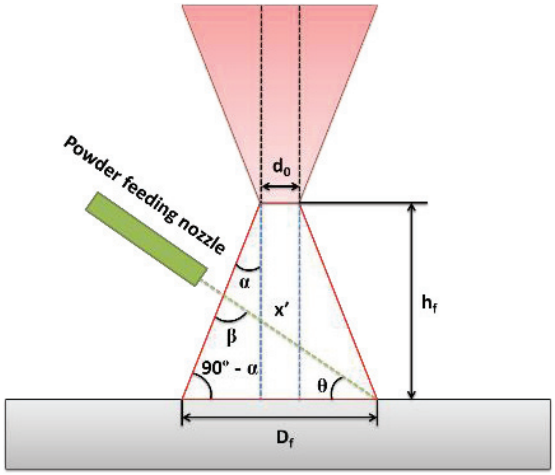

Fig. 2. Powder path in the defocused laser beam, x' marks the powder particles longest theoretical path inside the laser beam; h_f is theoretical focal point level distance to the substrate, d_0 is focal point diameter at the focal level, D_f is the focal point diameter at the substrate material level, α is the optics refraction angle to the laser and θ marks the powder feeding angle.

Powder particle temperature rise inside the laser beam is mainly dependent on the feeding angle, the particle velocity, the particle size, and the laser beam's intensity as determined by several research papers by Neto and Vilar (1998), Huang et al. (2005), Fu et al. (2002), Schneider (1998), Neto and Vilar (2002), Li et al. (1995), Liy and Lin. (2003), Lin (1999). Using this main parameters and geometry from figure 2, following formula can be formed for calculating powder particles temperature:

$$T_{max} = T_0 + \frac{aI\pi r_p^2 \frac{D_f \sin(90-\alpha)}{v_p \sin(90+\alpha-\theta)}}{\rho \frac{4\pi r_p^3}{3} c_p} \quad (3)$$

Where, T_0 is initial temperature, the r_p is the radius of powder particle, ρ is density of powder material, c_p is the specific heat factor of the powder, a is absorption factor, I is laser the beam's intensity and v_p is particle velocity. This calculation uses the following boundary conditions:

1. The powder particle is moving at a constant speed.

2. The powder particle travels through the laser beam from one to opposite corner of the laser spot
3. The gravitation effect on the powder particles' flight path is disregarded
4. The laser beam's power intensity through the laser beam is treated as constant
5. Intensity and absorption is treated as constants

1.2. Clad bead geometry

Clad bead geometry has to full fill some requirements that cladding can be successful. Firstly, the clad bead should have a low dilution, so that the clad bead obtains the desired material properties e.g. hardness. Secondly, the clad bead needs to have a proper cross-sectional geometry, low wetting angle (>120°), sufficient height and width. These geometrical properties determine e.g. how well the overlapping can be performed, or how well the different shapes can be formed, when cladding is used as a direct energy deposition process (DED). However, both matters, dilution and the clad bead geometry, are dependent on the process parameters. Bruck (1987), Weerasinghe and Steen (1987), Kaplan and Groboth (2001), Ion (2005), Han et al. (2004), Qian et al. (1997), Yellup (1995), de Oliveira et al. (2005), Mazumder et al. (1999), Boddu et al. (2001), Capello et al. (2005), Lewis and Schlienger (2000), Hoadley and Rappaz (1992)

In order to metallurgical bond to form between the clad bead and the substrate, a small amount of substrate material must be melted. However molten substrate material dilutes the chemical composition of the additive material and thus it is preferable that melting of substrate is kept at minimum. For laser cladding this typically refers to a dilution of under 10 %. Dilution is highly dependent on the process parameters, mainly the laser power, cladding speed, and powder feed rate, the same parameters that define mass-energy balance .In its simplest form, it can be stated that if there is too much energy compared to the fed additive material, the dilution increases, and vice versa. This is mass-energy balances effect to dilution. Thus by increasing powder feeding the process, the dilution can be decreased and increasing in the laser power increases dilution, if other parameters are held at constant level. However, no pure laser power but also laser intensity also affect to the dilution. High intensity can cause an increase of dilution through vaporization. If the intensity is high enough so that even small amount of material evaporates, the process resembles more a laser alloying than cladding due to high dilution, as Vollertsen et al. (2008) demonstrates in their study. Bruck (1987), Weerasinghe and Steen (1987), Kaplan and Groboth (2001), Pelletier et al. (1993), Ion (2005), Han et al. (2004), Qian et al. (1997), de Oliveira et al. (2005), Fathi et al. (2006), de Lange et al. (2005), Kim and Peng (2000), Huang (2011), Zhao et al. (2003)

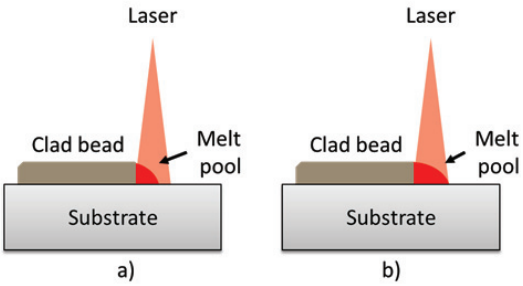

Fig. 3. a) When the cladding speed is high the melt pool formed is small and the laser beam has a direct contact with the substrate material. b) By reducing the cladding speed, the melt pool becomes larger and pushes forward. In the latter case the clad bead then "shields" the substrate material against the excessive exposure to the laser beam.

Cladding speed effect to dilution is two folded, at high cladding speeds mass-energy balance determines mainly the dilution, as Zhao et al. (2003), Huang (2011) and. Kim & Peng 2000, and thus increase of speed decreases dilution. However at low cladding speeds melt pool can work as protective shield against laser light, figure 3, and decrease of cladding speed can decrease dilution, as Qian et al. (1997), Fathi et al. (2006) and de Lange et al. (2005) pointed out. Then increase of cladding speed reveals substrate material to laser light and thus enables laser to melt substrate

material directly, which can increase dilution, figure 3. So two different mechanisms determines cladding speeds effect to dilution.

Wetting angle of clad bead should be 120º or higher so that when the clad beads are overlapped they form a uniform structure. If the side angle is considerably smaller than 120º, the possibility of trapping impurities or the formation of inter-run pores between the clad beads increases significantly. Another important geometrical requirement is that the clad bead has width and height. These aspects define, how many clad beads must be done next to each other and/or on top of each other so that the desired area and volume is covered. The width of the clad bead is mainly defined by the laser power, cladding speed, beam diameter, or scanning amplitude of the laser beam and clad bead's height is, in turn, dependent mainly on the clad material mass feed rate, cladding speed, and laser power. Increase in the laser power causes modest widening of the clad bead, and an increase in the cladding speed modest narrowing of clad bead. The Increase in the mass feed rate naturally increases the clad bead height. When there is more material, higher clad bead can be formed. The cladding speed has the opposite effect. When the cladding speed is increased the clad bead height decreases as less additive material is fed in per unit length (g/mm). Bruck (1987), Weerasinghe and Steen (1987), Picasso et al. (1994), Qian et al. (1997), de Oliveira et al. (2005), Hoadley and Rappaz (1992), Fathi et al. (2006), Huang (2011), Zhang et al. (2007), Huang and Yuan. (2012)

1.3. Laser cladding with scanning optics

Laser cladding using a scanned beam is quite a similar process than laser cladding using static optics. The main difference comes from the manipulation of the laser beam. In laser cladding with scanning optics the laser beam is manipulated with a scanner so that the laser's area of influence can be increased, figure 4. Thus, the laser beam material interaction area is determined by two factors: scanning amplitude and spot size, figure 4. In turn, laser cladding with static optics the size of the interaction areas is determined only by the spot size. The laser beam material interaction area is defined mainly by the scanning amplitude. As the melt pool width follows the laser beam material interaction area, the clad bead's width can be adjusted through the scanning amplitude. Thus, the adjustment of the scanning amplitude enables considerable flexibility to affect the clad bead's geometry.

When the laser cladding is done using scanning optics, there is a difference in energy input mechanism compared to cladding done by using static optics. With scanning optics energy input takes place through a relatively small laser spot which is scanned rapidly over LBMI. Thus, local laser energy input is high, but at average over heat input in this area is again relatively low. This dual characteristic of the energy input separates cladding with scanning optics from the cladding with static optics and sets some new limits to the process parameters.

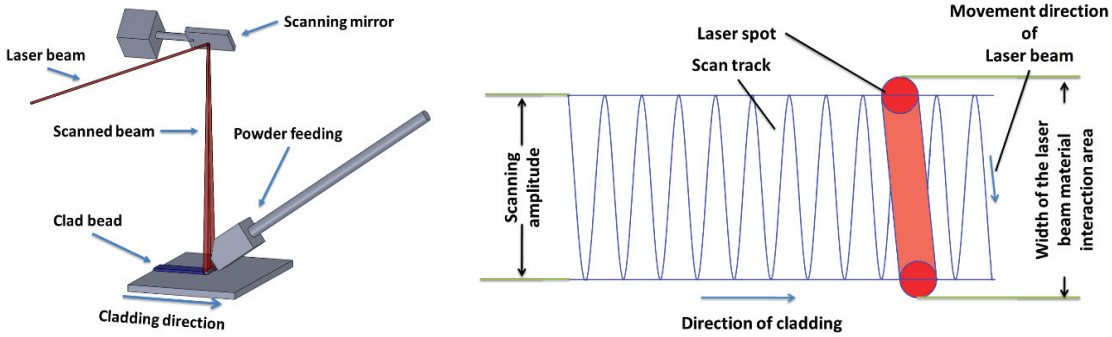

Fig. 4. Principal setup of the laser cladding process and scanning amplitudes and laser spot relation to the area of laser beam material interaction (LBMI)

2. Experimental setup

The laser used was a solid-state ytterbium fiber laser manufactured by IPG model YLR-5000-S. The used focusing optics was Precitec YW50 welding head with 150 mm collimator lens, 500 mm focusing lens and 150 µm diameter fiber. An ILV DC scanner was amounted between the collimator lens and the focusing lens. The cladding process

was monitored using video imagine equipment with Cavilux laser illumination system. The Cavilux illumination system illuminates the videoed target at a wavelength of 808 nm. Two different cameras were used in these tests, in test 1 to 3 a normal CCD camera was used, and in test 4 a high-speed camera was used. The CCD camera frame rate was 20–25 fps and the high speed camera´s 2000 fps. The feedstock material used in all the test was an AISI 316L stainless steel powder, particle size of 53 to 150 µm, and the substrate material used was 6mm standard S355 structural steel plate The scanner that was used in this study was an ILV DC linear scanner. This scanner model has a power adjustment feature. The laser power can be adjusted at 32 points according to location where the scanning mirror is directed.

3. Results

3.1. Scanning optics usability in laser cladding – first test serie

Scanning amplitudes adjustments effect to the width of the clad bead was studied using three different scanning amplitudes, 3.1 mm; 9.6 mm and 17.5 mm, which produced clad beads width of 5.3mm; 13 mm and 19 mm. All these test were made using figure 6b type power adjustment profile. The scanning amplitude defines not only the clad bead's width but also the overall geometry of the clad bead, e.g. height, dilution and side angle, Figure 5. From video imagine there was noticed dynamic movement in the melt pool caused by moving laser spot. This phenomena occurred when laser vaporized small amount of material and as this dent moved along with the scanned laser.

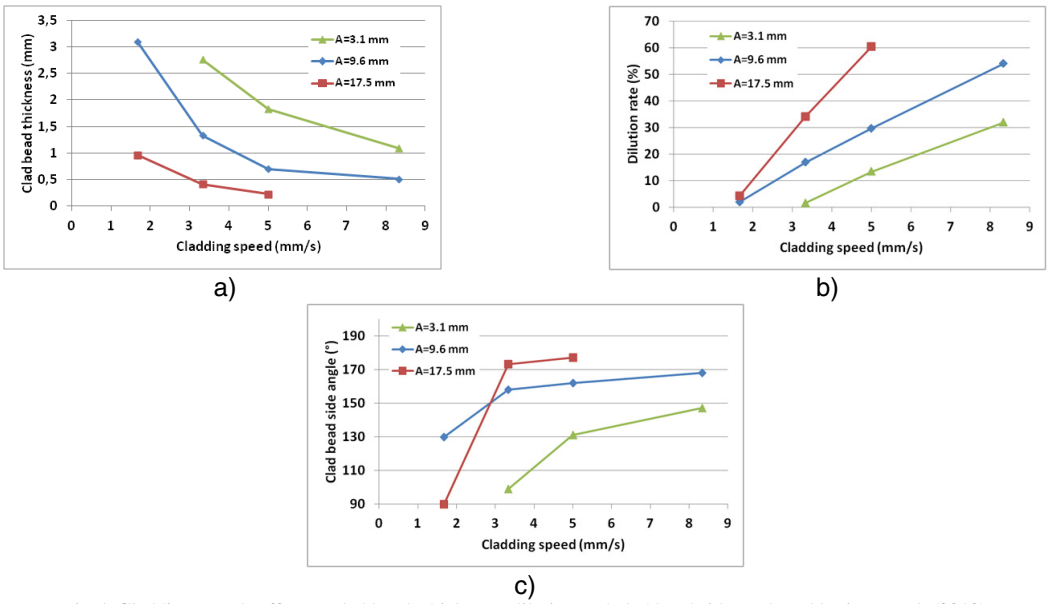

Fig.5. Cladding speeds effect to clad beads thickness, dilution and clad bead side angle Pekkarinen et al. (2012)

3.2. Power adjustment in laser cladding – second test series

In this test series six different power adjustment profiles (PAP) were tested and one where no power adjustment was used. Power adjustment in scanner based laser cladding has two functions. Firstly, it can be used to stabilize the cladding process. It was noticed that when no power adjustment were used heat input pattern was so called viper teeth pattern, where the energy input is higher at the far ends of the scanning amplitude. This is caused by change in the direction of movement of scanning mirror, when the mirror velocity is decelerated, stopped and accelerated at end of scanning amplitude. This creates a situation of excessive energy input at scanning amplitudes far ends which in turn can cause instability (vaporization) at the melt pool edge areas. This vapor formation disturbs the cladding process and increases the dilution at this edge region.

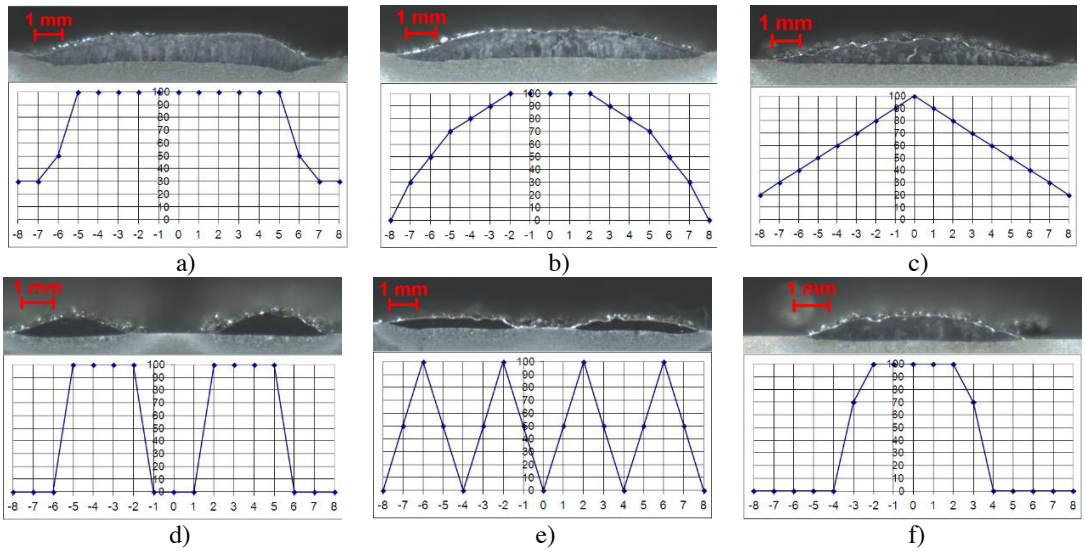

Fig. 6. Tested power adjustment figures.

Secondly, using different power adjustment patterns different clad beads geometries can be created, figure 6. As the energy input is adjusted across area of laser beam material interaction, thus there is different amount of energy to melt additive material in different locations in side the melt pool. So, through this mechanism the cross section geometry of the clad bead can be adjusted. In this test series, six different power adjustment profiles were used and the corresponding geometries are presented in figure 6.

3.3. Two folded energy input and process stability – third test series

As scanned laser beam imports energy trough small laser spot, both laser spot size and scanning frequency affect the process stability. All these test were made using figure 6b type power adjustment profile. With both of these parameters (spot size and frequency) excessive vaporization inside the melt pool was noticed, when certain parameters were used, figure 7 high dilution. When vaporization occurred in the melt pool a small shallow keyhole was found where the vapor flow rise. Vapor flow rising from the keyhole prevented the additive powder material from reaching the melt pool, which in turn caused the dilution to increase when additive material was not able to reach the melt pool.

It was noticed that using low, below 40 Hz, scanning frequency, a significant amount of vaporization occurred inside the melt pool, forming a keyhole. Then keyhole dug in the substrate material increasing the dilution well above 20 %. 40 Hz and higher scanning frequencies ensured stable process where no vapor formation was noticed, then specific local energy input was lower than 2.42 J/mm2. When one sweeps local specific energy input was higher than this vaporization occurred.

If the intensity was too high, vaporization can occur even though laser is scanned at high frequency (100 Hz). The high peak intensity of laser spot caused a small keyhole to form, which effetely ruins the clad quality (high dilution). It was determined that peak intensity of 191 kW/cm2 is low enough to ensure stable cladding process, at scanning frequency of 100 Hz. In turn peak intensities higher than this causes unstable cladding process

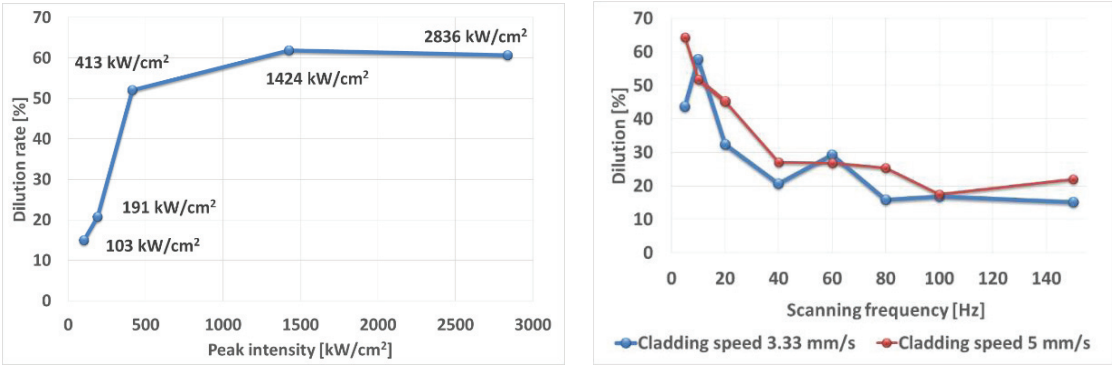

Fig. 7. Intensity's and scanning frequency's effect to dilution Pekkarinen et al. (2012)

3.4. Powder cloud behavior under the scanned laser beam – fourth test series

The powder cloud's stability was noticed to be dependent on three things, the powder feeding angle, the powder feeding gas flow rate, and the scanning amplitude. All these test were made using figure 6a type power adjustment profile. The powder cloud behavior was more stable at higher gas flow rate and scanning frequency and with powder feeding angles of 40 º and 60 º degrees. In turn 70 º and 50 º degree feeding angles caused significant instability to the powder cloud. The effect of the scanning frequency to stability is the same as in the melt pool case. The high frequency equalizes the local heat input and thus a more stable process is achieved. Higher (6 l/min) feeding gas flow rate decreased probability to excessive vapor formation in powder cloud. If powder material started to vaporize low (3l/min) feeding gas flow rate did not blew the vapor plume away and it formed stationary vapor plume which started to absorb energy to itself. Thus the vapor acts as a self-reinforcing factor in the powder cloud's instability. When the gas flow rate was higher (6l/min) it blew the formed vapor away and through this mechanism stabilized the powder cloud. The powder cloud's stability had a significant effect on the clad bead dilution rate. When vaporization occurred in the powder cloud it significantly affects the powder material's access to the melt pool. Discharging vapor pushed the powder stream aside from its original flight track and thus the powder particles did not reach the melt pool. This was noticed when the clad beads deposited cross-section areas were compared. When even a slight amount of vaporization was noticed, the deposited cross-section area was decreased and correspondingly the dilution rates increased. This is because the energy of the laser beam is then diverted to melting the substrate material instead of the additive powder material. When this vaporization occurred, it created a sort of plume on top of the melt pool, which in turn started to emit light at 450 to 650 nm wavelength range. The intensity of light emitted by the powder cloud was noticed to have direct correlation to the vaporization / plume size. Correspondingly; if there was no vaporization detected in the powder cloud, the measured emission was very low.

4. Discussion

When scanning optics is used in laser cladding almost all the basic priceless of the process remain the same. Main difference between scanning and static optics comes from the energy input mechanism. When energy is introduced to the process through small high intensity owning laser spot instead of large low intensity owning spot it bound to have impact to the process mechanics and the outcome of the process. Cladding speeds effect to dilution is good example difference in process mechanism. When cladding speed increases dilution rates increases remarkably quickly. This is because at low cladding speed the melt pool grows larger and pushes forward to cladding direction, which in turn covers the laser beam area of interaction. In this way, the laser beam does not interact directly with the substrate material. On the other hand, when the cladding speed is higher the melt pool size reduces and draws back against the cladding direction. Therefore, when the melt pool does not cover the whole laser beam material interaction area, the

laser can interact directly with the substrate material. Hence, when this high intensity laser spot can react directly with the substrate material the substrate melting increases significantly and thus dilution increases. This is the way how at low cladding speeds the melt pool can, in one sense, act as a "protective shield" for the substrate material against the high intensity laser beam.

Dilution case demonstrates quite well effect of energy inputs duality. Because energy is imported trough small spot slight change in melt pool behavior induces large change in dilution. However material vaporization causes even bigger effect to dilution. When locally energy input exceeds threshold levels, too high specific local energy input or intensity, laser is able to vaporize material and create shallow keyhole. This enable laser to dig in to the substrate material which increases dilution significantly. Even though overall energy input is the same with 20 Hz and 100Hz scanning frequency, locally energy input is differs significantly. Add to this powder feeding creates its own challenge for cladding using scanning optics. Steep powder feeding angle or low powder gas flow rate exposes powder material to vaporize during the feeding. Powder vaporization is significant challenge for process control, because vaporization of material prevents additive material access to melt pool and thus ruins the cladding outcome. For this reason cladding process phenomena's and development of dilution must be reviewed trough both mass-energy balance (macro level) and local energy input (micro level). Because of this process adjustment is more complex.

As there is many restrictions in this process there are nevertheless many opportunities. Ass it has been shown that power adjustment can be used to stabilize the process but also to modify the clad bead geometry. Needs for clad beads geometry can vary greatly depending on the application and thus possibility to modify clad beads geometry increases cladding process flexibility. For instance if large areas need to be coated flat middle section in clad bead is preferable so that coating layer would be as even as possible but side angle of clad bead should be over 120°. On the other hand for building up shapes (Direct Energy Deposition process) it might be preferable to create high and narrow clad beads. These both can be done using scanning optics, figures 5a and 6c & f, by modifying scanning amplitude and powder adjustment profiles.

Direct Energy Deposition process (DED) could benefit a lot on usage of scanning optics. In additive manufacturing different wall thickness and shapes are needed to build and scanning optics could offer flexible way to doing this. For instance thicker walls could be build up using fewer clad beads and so reducing risk of clad beads intermediate pore formation. Another surface treatment process where scanning optics could be beneficial is laser alloying. Process instability could be also exploited in deep penetration alloying. If parameters were selected so that shallow keyhole is formed to the substrate material it would enable mixing of alloying elements to the substrate material in much deeper scale. However both of these maters would need further studying.

In the end scanning optics enable lot of flexibility for process adjustment and to the adjustment of clad beads geometry but in return it also bring new type of challenges to the energy input. When scanning optics is used process energy input must be viewed firs in micro level (process stability and melt pool behavior) and after that in macro level (mass-energy balance). After all process stability effect to dilution is much higher than mass-energy balances.

5. Conclusions

Scanning optics enables flexibility to the cladding process. When the scanner enables numerical control of both the scanning amplitude and scanned beams laser power, the geometry of clad bead can be numerically adjusted more freely. Clad beads width and over all geometry can be adjusted by adjusting scanning amplitude and power adjustment which in turn enables more versatile usage of laser cladding.

Power adjustment has an important part in stabilizing the melt pool behavior. As the oscillating mirror experience dwell time at mirrors movements turning point it also causes excessive energy input at the borders of the scanned area. It is important that energy input is compensated with the power adjustment across the clad layer.

Powder cloud is also prone to excessive vaporization under the scanned laser beam. A steep powder feeding angle, low feeding gas flow, and low scanning frequency can cause powder material vaporization in a powder cloud. Vapor formation can be observed by measuring the intensity of the powder cloud's emitted light in a wavelength range of 450 to 650 nm. High intensity glow at this wavelength range indicates powder material vaporization.

Cladding process stability has a significant effect on dilution of the clad bead. All instability in the cladding process increases the dilution. Stability affects the dilution in two ways: firstly, the laser beam is able to penetrate deeper to

the substrate material. This naturally increases the melting of the substrate material and thus the dilution. Secondly, vaporizations causes vapor flow which disturbances the additive material feeding.

Melt pool behavior has a significant effect on dilution. Since the scanned beam has a relatively high local intensity, it is preferable that the laser beam has minimal direct contact with the substrate material since this increases the dilution. Thus lower cladding speeds is recommendable because at lower cladding speeds melt pool covers better the lasers area of interaction and laser has less direct contact with the substrate material.

The importance of parameter selection increases when the laser cladding is done using scanner optics. This is due to the dual characteristics of the heat input. Even though the scanned laser beam imports energy to a large area and on average the intensity is relatively low but locally laser beam still has a high intensity. The local intensity peak sets limits to the scanning frequency and the laser beam's spot size or intensity. High scanning frequencies evens out the unevenness of the energy input caused by this local high intensity.

Acknowledgements

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