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Procedia CIRP 6 (2013) 498 – 503
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The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)

Influence of the interaction of focused laser beam and gas-powder stream on the quality of laser processing

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Abstract

Laser processing technologies like alloying, cladding and rapid prototyping that are based on blowing of gas-powder mixture in the zone of laser processing are very dependent on the alignment of caustic surface (conventional surface that surrounds laser beam) and gas-powder mixture regarding the workpiece surface. Deep knowledge of its behavior is very important for the technologies that use coaxial introduction of gas-powder mixture into the processing zone.
By means of numerical modeling with further experimental verification it was found that the shape of the gas-powder stream and its cross-section could be varied with help of the nozzles of various inner shapes. Further investigation of laser cladding technology by means of experiment planning techniques showed statistically significant influence of the position of caustic surface, and gas-powder mixture and the workpiece on the productivity (the size) and quality (presence of cavities) of the clad.

Selection and/or peer-review under responsibility of Professor Bert Lauwers

Keywords: laser cladding; experiment planning; nozzle

1. Introduction

The influence of the properties of gas-powder transportation system that form a gas-powder stream in the zone of laser beam interaction with a workpiece surface on the productivity and quality of laser sintering of powder materials with solid base material was the scope of interest for many researchers [1-4]. In order to implement the technology of directed laser "growing". It was recommended that coaxial with laser beam delivery of gas-powder mixture should be used to minimize the microstructure defects. It does not matter where laser beam travels- the position of powder stream regarding the laser beam will remain unchanged. In general, only basic numerical models [1] were used for the investigation of laser beam — gas-powder stream interaction that does not explain the laws of distribution of concentration of powder density in the gas-powder stream depending on the distance from nozzle exit, nozzle configuration etc. This lack of knowledge could be fulfilled using numerical computations.

Having known the properties of gas-powder stream and how to manipulate it, along with the parameters of laser irradiation it is possible to determine optimal technological regimes that would result in the laser sintering of parts with pre-defined level of quality and productivity.

This paper is dedicated to the solution of such problems.

2. Experimental set-up and methodology

As it was mentioned earlier, the research was based on two methodologies: numerical simulation of gas-powder jet formation employing nozzles with various inner profiles and investigation of laser cladding using experiment planning techniques. The behavior of gas-powder jet at different working pressures of transport and protective gas was described by Eulerian model and numerical solutions for powder-jet profile and powder distribution within the defined cross-section were found using software Ansys CFX [5]. The choice of the Eulerian model is explained by the fact that small powder fractions (10-100 μm) are used at laser cladding.

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Selection and/or peer-review under responsibility of Professor Bert Lauwers
doi:10.1016/j.procir.2013.03.062

The overall turbulence for two phases (gas and powder particles) was calculated with standard $\kappa - \varepsilon$ turbulence model. Obtained numerical solutions were compared with experimental data.

Series of experiments were conducted using the equipment presented in Fig.1. A two-telescope system was placed at the exit of laser resonator to control focal spot and profile of the caustic surface, along with rotating mirror and focusing system with focusing length of 100 mm. Gas and powder supply unit equipped with changeable coaxial nozzles that had different angles γ (Fig. 1) was mounted at the bottom of the focusing unit (Fig. 2).

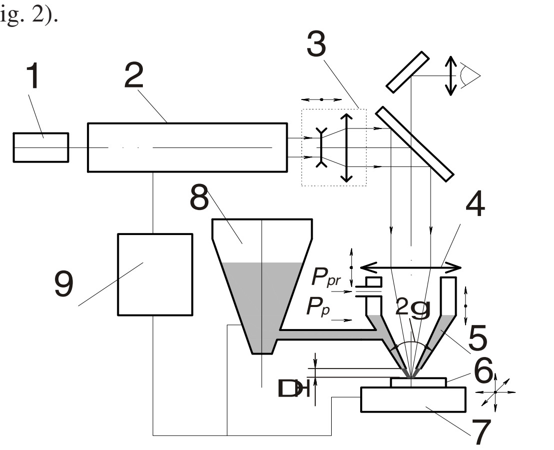


Fig. 1. Industrial laser equipment: 1- assist laser; 2- working laser 200 W; 3- telescope; 4- focusing objective; 5 –coaxial nozzle; 6 – workpiece; 7 – worktable with 3 coordinates; 8- powder feeder; 9 – control unit.

The scheme of experiments was obtained using experiment planning technique and each trial was repeated trice into every control point. PGSR-3 powder (10-60 μm) was used for cladding and air was used as a transporting gas.

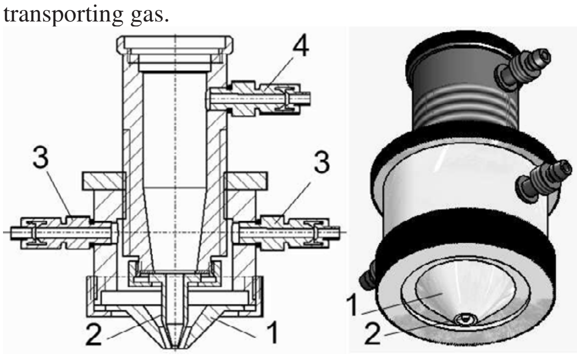


Fig. 2. Schematic view (a) and a 3-D view (b) of coaxial powder supply unit into the processing zone: 1,2 – replaceable nozzles; 3- powder and transportation gas inlets; 4- assist gas inlet.

3. Experimental results and discussion

The following steps were taken to conduct numerical simulations:

– design of 3-D physical model of powder supply and postulation of boundary conditions
– meshing of the 3-D model
– direct computation of powder particles trajectories and their analysis.

Implementation of Ansys CFX for the simulation of gas-powder stream helps to visualize powder particle paths (Fig. 3a) and powder particle concentration's distributions (Fig. 3b). Numerical simulation shows that spatial distribution of powder concentration in planes collinear with and perpendicular to the central axis of gas-powder stream (laser beam) significantly depends on the values of nozzle forming angle γ.

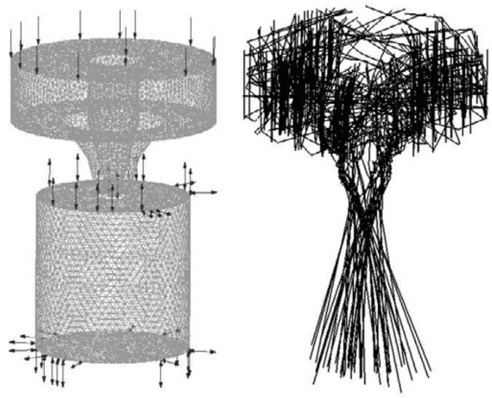


Fig.3. Mesh (a) and a particles trajectories (b) of coaxial powder supply system

The angle γ varied in a range from 30 to 50 degrees and in all cases the distribution of powder concentration changed from ring-shaped to round-shaped depending on the distance from the nozzle exit to the section plane (Fig. 4, Fig. 5). the transformation of ring-shaped distribution into the round-shaped starts at the "focusing" point of gas-powder stream.

Moreover, simulations show that the increase of forming angle γ decreases "focusing" length (distance from the nozzle exit to the narrowest part of gas-powder stream). Further experiments proved this hypothesis (Fig. 5) . It was found that minimal cross-section of gas-powder stream lies downstream of the point where laser beam and gas-powder stream central axis intersects with lines that firm the inner shape of the nozzle. This is possibly due to the pressure of protective gas (P_{pr}=1 bar, Fig.1, Fig.2) in the inner part of powder supply nozzle.

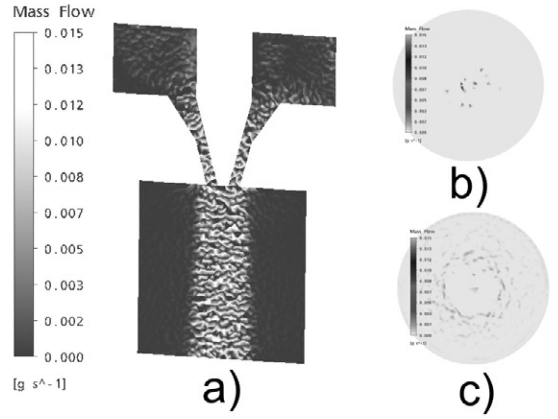


Fig. 4. Distribution of the concentration of powder mixture along the axis of distribution (a) and in cross-section (b, c) at the nozzle exit (b) and in powder focusing spot (c).

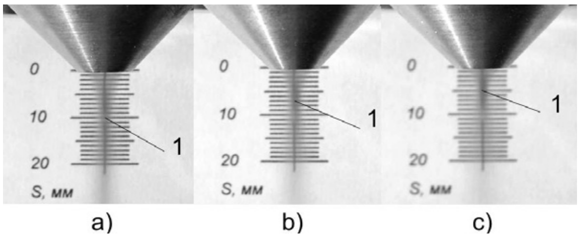


Fig. 5. General view of gas-powder streams after the nozzle exit , where a) - 30° nozzle forming angle; b) 40° nozzle forming angle; c) - 50° nozzle forming angle; 1- minimal cross-section of gas-powder stream.

Comparison of the results of numerical simulation and experimental data shows that altering values of the forming angles it is possible to control the distance from the nozzle exit downstream where the cross-section of gas-powder stream will be minimal, and at the same time it is possible to pre-define the curvature of the envelope surface of the stream. For a given design space a mutual positions of the processed workpiece and gas-powder stream were established that could be used for the development different processing schemes:

• "blowing" of powder in the molten base material when the workpiece upper surface rests above the "focusing" point of gas-powder stream (ring-shaped gas-powder stream is used) and their further re-melting

• "blowing" of the molten powder in the molten base material (round-shaped gas-powder stream is used) when the concentration of powder particles is not enough to "block" laser beam;

• "blowing" of the molten powder in the solid base material when the concentration of powder particles is enough to "block" laser beam.

The influence of the configuration of gas-powder stream and irradiation regimes on the quality of laser cladding and laser sintering was investigated using experiment planning technique. In order to build the quadratic model (1) a Box-Behnken design [6] was used which is rotatable (i.e. Model (1) predicts the behaviour of the response factor with similar accuracy when moving from the centre of the plan).

$$y = b_0 + \sum_{i=1}^{i=k} b_i x_i + \sum_{i\neq j=1}^{i\neq j=k} b_{ij} x_i x_j + \sum_{ii=1}^{ii=k} b_{ii} x_{ii}^2 \quad (1)$$

where: k - number of technological factors;

b_0, b_i, b_{ij}, b_{ii} - regression equation coefficients;

i, j - indexes

The technological factors were (Table 1 shows levels of variation for technological factors in the encoded and natural scale) :

γ — forming angle (X1);

mp –powder mass flow (X2);

Vx – speed of the base material (X3);

ΔH – position of the workpiece regarding the nozzle exit (X4),

whereas response factors were : geometry of a single clad: height (HCL) and width (WCL), uniformity of the inner microstructure of the sintered primitives (QCL) – inner porosity of the clad. The latter was determined as a ratio of the sum of the defected layers' areas (pores, microcracks etc.) on the images of micro sections (to the overall area of the image.

Computational domain shown in Table 1 is presented in the encoded scale (factors take values -1, 0 and +1 and are used for calculation of the coefficients of numerical model (1) for each response factor) and in natural scale. It is possible to convert values of technological factors between scales.

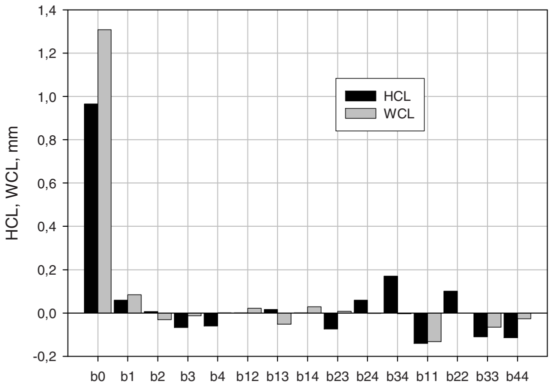
Since our coaxial nozzles can be moved regarding the focusing objective (Fig.1 and Fig.2) — value of ΔH, focused laser beam density in the processing zone remained constant — the waist of the caustic surface was 0,7 mm whereas the length of this surface was 10 mm.

According to the designed plan 27 experiments were carried out with triple repetition in each point of the experiment plan. Statistical processing of the results of experiments showed that rows of the dispersions (for each response factor) were similar, i.e. Calculated Cochrane criteria G_{calc} (for the level of importance accepted in machine-building α=0.05, degrees of freedom f=2 and number of experiments N=27) were less than tabulated value G_{tabl}=2.2. Moreover, there were calculated the coefficients of the regression equations (shown in Figure 6 as rank diagrams), and the hypothesis of the adequacy of received numerical models was verified. All regression coefficients were statistically important and hypothesis of the adequacy of the models was verified (calculated values of Fisher criteria F_{calc} were much less than tabulated ones - F_{tabl}=3.17 (for the level of importance accepted in machine-building α=0.05, degrees of freedom f_1=54 and f_2=2).

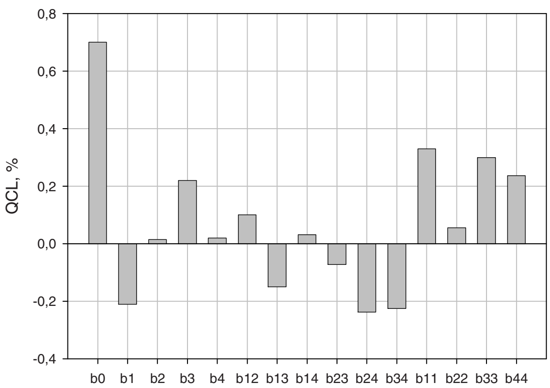
Obtained numerical models (1) represented in Figure 5 as rank diagrams are "black-box" models and will inherit any sound explanation of their behavior. Coefficient value and its sign stand for the degree and direction of influence of the technological factor on a response factor.

Table 1. Level of variation of technological factors

#	Levels of variation and intervals of change, Technological factors	Code	Independent variables			
			γ	mp	Vx	ΔH
			x_1	x_2	x_3	x_4
1	Dimension	unit	Grad	g/s	mm/s	mm
2	Ground level	0	40	0.3	2	5
3	Interval of variation	1	20	0.1	1	2
4	High level	+1	50	0.4	3	7
5	Lower level	-1	30	0.2	1	3



a)



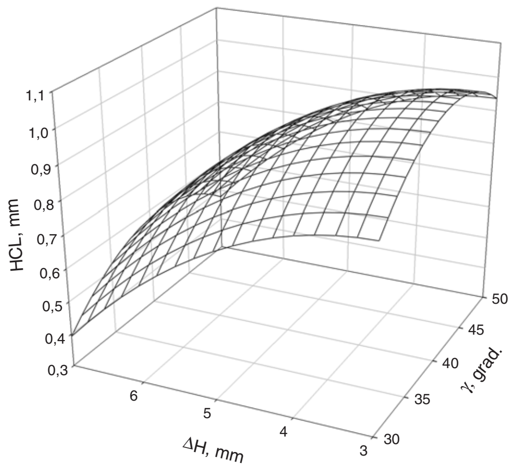
b)

Fig. 6. Regression coefficients for laser sintering model, where: a) – height and width of the clad from technological factors; b) - coefficients responsible for microstructure of clad

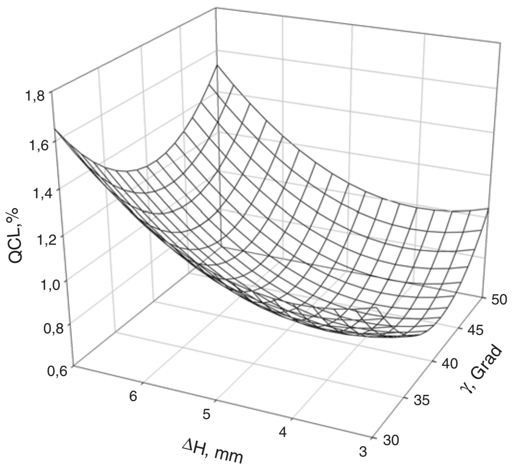
Maximum linear and quadratic influence on the dimensions of the clad layer and the uniformity of microstructure is caused by:

- nozzle forming angle (coefficients b_1 and b_{11} from Fig. 6);
- workpiece travel speed (coefficients b_3 and b_{33} from Fig. 6),
- mixed influence (coefficient b_{13} from Fig. 6) and quadratic influence of all factors.

Influence of nozzle forming angle on the height and uniformity of microstructure of the clad layer is bidirectional (Fig.6). Fig. 7 shows the dependencies of the HCL and QCL from technological factors when mp= 0.2g/s and Vx = 1mm/s.



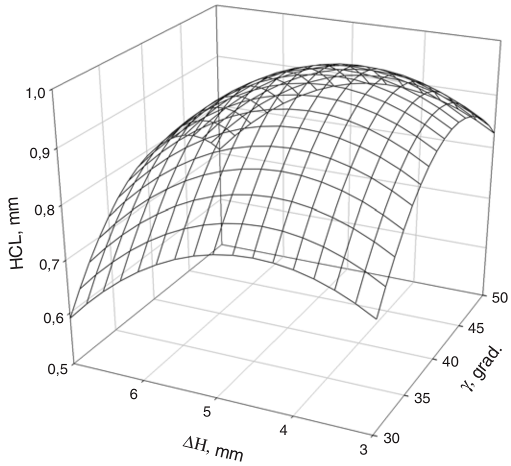
a)



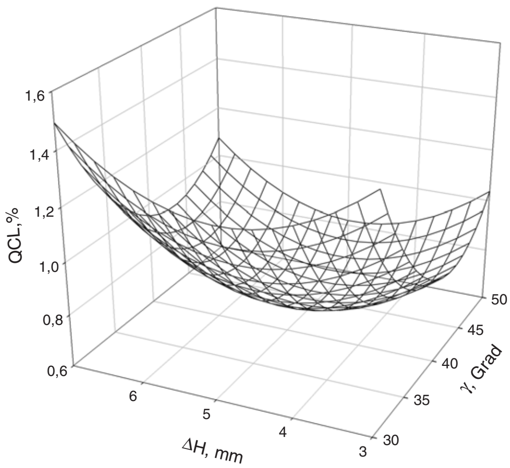
b)

Fig.7. Dependencies of HCL (a) and QCL (b) from the distance from nozzle exit and nozzle forming angles when mp = 0.2g/s and Vx = 1mm/s

The minimum number of pores in the clad layer and maximum processing quality was in the case when the nozzle forming nozzle was equal to 40° and, what is more, the minimum value of QCL is observed when focusing of the powder stream starts on the surface of the workpiece (ΔH=5 mm) and powder is blown into the liquid pool with further re-melting.



a)



b)

Fig. 8. Dependencies of HCL (a) and QCL (b) from the distance from nozzle exit and nozzle forming angles when mp = 0.2g/s and Vx = 2mm/s

The increase of the processing speed up to 2 mm/s forms clad layer with high quality by scheme of blowing of molten powder into the molten base material (minimal value on the dependency of QCL=f(ΔH,γ)) (Fig.8) when ΔH=6 mm. The increase of nozzle forming angle leads to the increase in WCL, HCL and QCL (Fig.6, Fig.7), that is explained by the increase of the area of cross-section of the gas-powder stream and lack of the energy of laser beam for total re-melting of powder and surface of base material. The same situation is observed when the value γ decreases: a huge amount of powder does not creates good bonding between powder and molten surface of base material.

While the processing speed increases the extremum of functions HCL=f(ΔH,γ) and QCL=f(ΔH,γ) shift proportionally with the increase of ΔH (Fig.6, Fig.8). The values of HCL decrease with decreasing of Vx.

This is due to the changes in power density that cannot handle with melting of powder in the "ring" that is delivered into the processing zone.

Analysis of the data shown in Fig.6 – Fig.8 in five dimensions (for each response factor) could be time-consuming, but using factors from Table 1 it could be seen that geometry of gas-powder stream and workpiece position regarding the "focus" of gas-powder stream are two most influential factors that QCL depends on. This could be seen from the values of the regression coefficients (Fig. 6) and gradients of surfaces HCL=f(ΔH,γ) and QCL=f(ΔH,γ) (Fig.7, Fig. 8).

Search for optimal regimes was done using the method of Lagrange multipliers [7]. MIN(QCL) was used as a target function in the design space (Table 1) at maximum values of HCL and WCL.

In some points of the design space there were conducted additional series of experiments that proved the validity and accuracy of numerical computations. The percentage of the defects in the clad layer decreased down to 0.18% (Fig. 9).

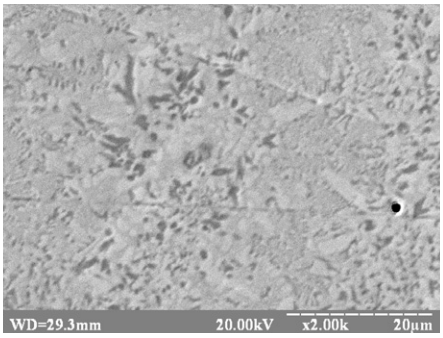


Fig. 9. Defects in the clad at optimal processing regimes (g=40°, mp=0.3g/s, V=1.9mm/s, DH=5mm)

A press roll was manufactured using established processing regimes (Fig. 10) that is used in printing industry.

Fig. 10. Press roll for printing industry

4. Conclusions

• It is possible to increase the quality of laser sintering (reducing the defects within the clad layer down to 0,18%) by means of optimization of the characteristics of gas-powder stream and the position of its waist regarding the upper surface of the workpiece.

• The most efficient method to influence the properties of gas-powder layer is to change the nozzle forming angle.

• In a designed factor space, at low laser beam power the number of defects of microstructure is reduced when gas-powder stream "focuses" on the surface of the workpiece upper surface causing simultaneous melting of the powder that enters into the caustic of gas-powder stream and workpiece surface.

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