Innovative Manufacturing Processes

Pulsed Laser Drilling

Laser drilling modelling

<u>Heat transfer:</u>

$$\boxed{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a}\frac{\partial T}{\partial t}}$$

Conservation of energy per unit volume

<u>Assumption:</u>
the drilling is considered as a one-dimensional process and the laser beam intensity is uniform:

1-D heat transfer

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Boundary conditions

$$-k\left(\frac{dT}{dz}\right)_{z=0} = J_o$$

$$as\ z \rightarrow \infty\ T = T_0$$

$$\boxed{T - T_o = \frac{2J_o}{k}\left(\frac{\alpha t}{\pi}\right)^{1/2} e^{-z^{2/4at}} - \frac{J_o z}{k}\left(1 - erf\,\frac{z}{2(at)^{1/2}}\right)}$$

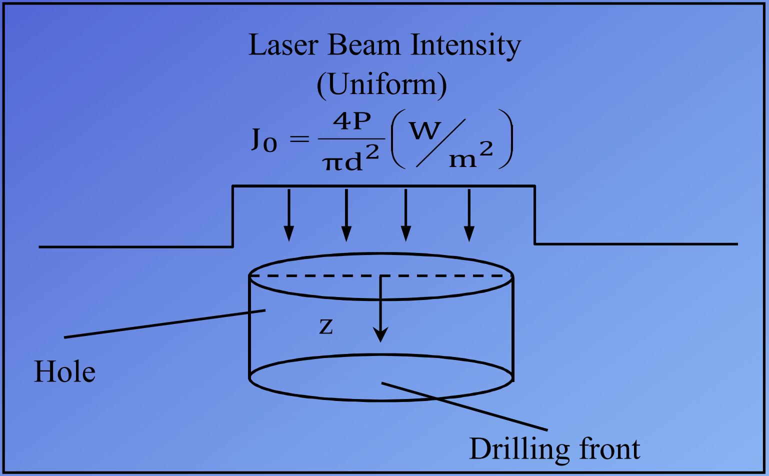
Temperature distribution inside the workpiece

REF: Salonitis, K., A. Stournaras, G. Tsoukantas, P. Stavropoulos and G.Chryssolouris, "A Theoretical and Experimental Investigation on Limitations of Pulsed Laser Drilling", Journal of Materials Processing Technology, (Vol. 183, No. 1, 2007), pp. 96-103.

Innovative Manufacturing Processes

Pulsed Laser Drilling

Laser drilling modelling



Heat balance at the erosion front:

Heat enters the workpiece	=	energy consumed for phase change	+	heat loss through conduction

$$\underbrace{\left[aJ_oA\right] = \left[mL\right] + \left[-kA\left(\frac{dT}{dz}\right)_{z=0}\right]}$$

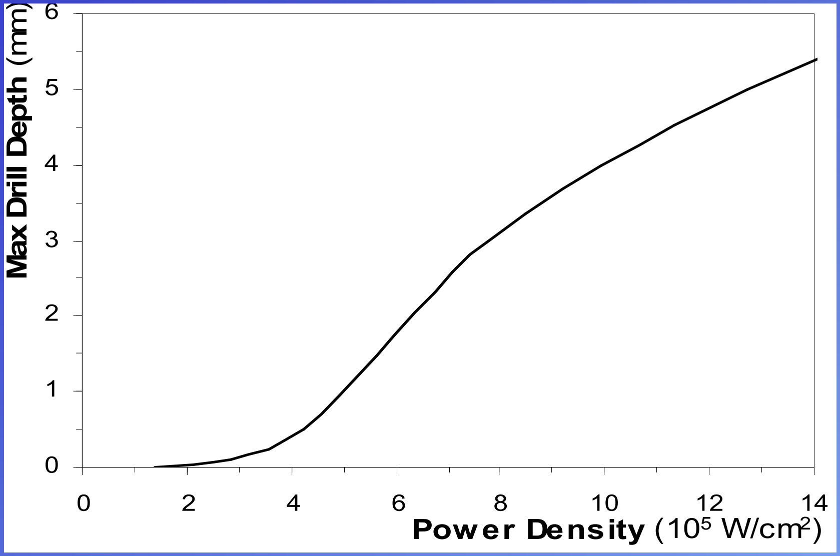
$$\boxed{aJ_o = \rho L\frac{\partial s}{\partial t} - k\left(\frac{dT}{dz}\right)_{z=0}}$$

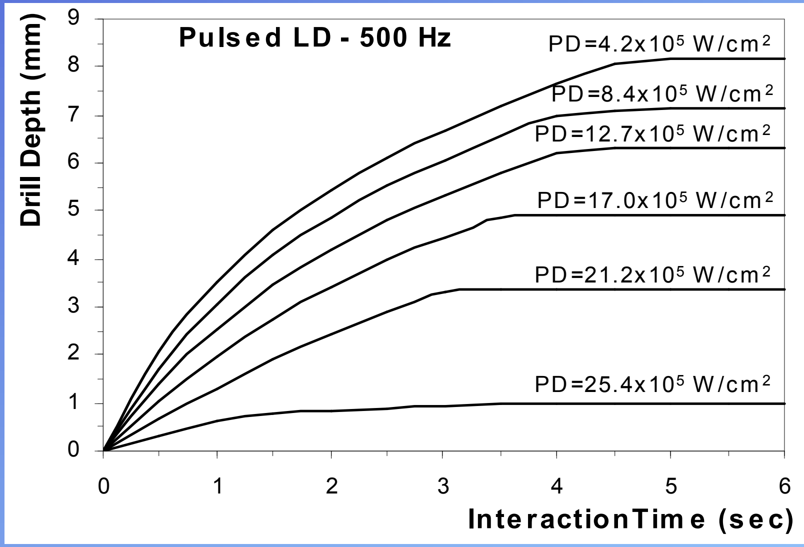
a: material absorptivity (-)
ρ: material density (Kgr/m³)
L: latent heat of fusion (KJ/Kgr)
k: thermal conductivity (W/mK)
T: temperature (K)

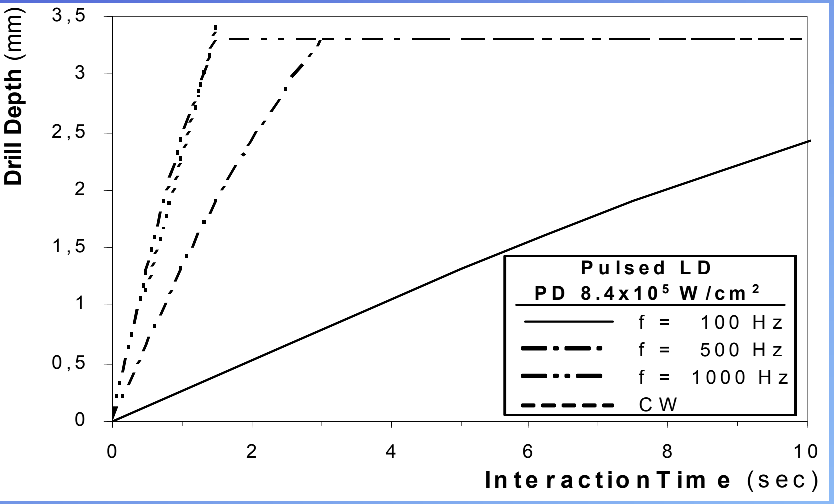
REF: Salonitis, K., A. Stournaras, G. Tsoukantas, P. Stavropoulos and G.Chryssolouris, "A Theoretical and Experimental Investigation on Limitations of Pulsed Laser Drilling", Journal of Materials Processing Technology, (Vol. 183, No. 1, 2007), pp. 96-103.

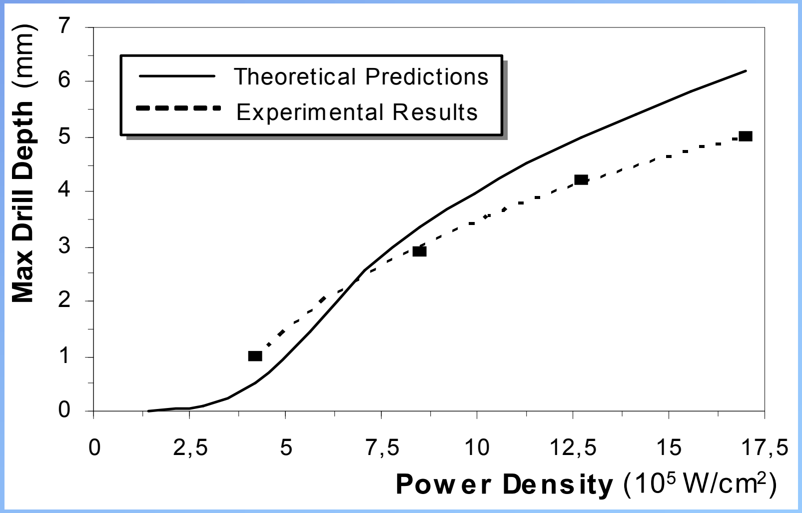
Innovative Manufacturing Processes

Pulsed Laser Drilling







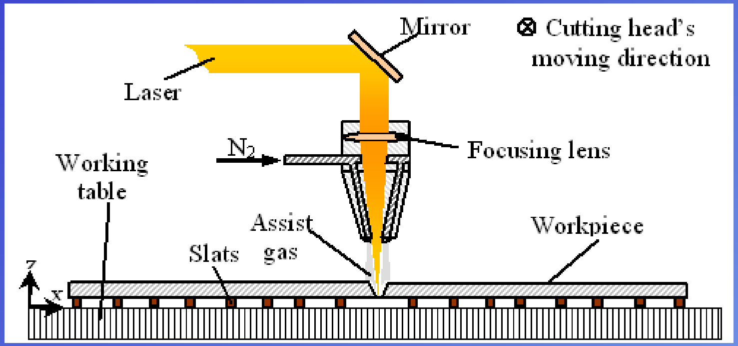


REF: Salonitis, K., A. Stournaras, G. Tsoukantas, P. Stavropoulos and G.Chryssolouris, "A Theoretical and Experimental Investigation on Limitations of Pulsed Laser Drilling", Journal of Materials Processing Technology, (Vol. 183, No. 1, 2007), pp. 96-103.

Innovative Manufacturing Processes

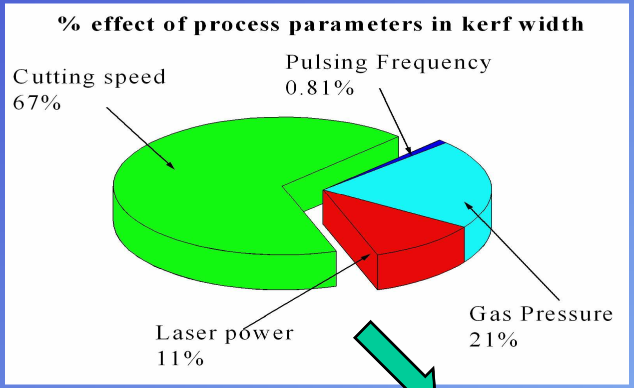
Laser Cutting

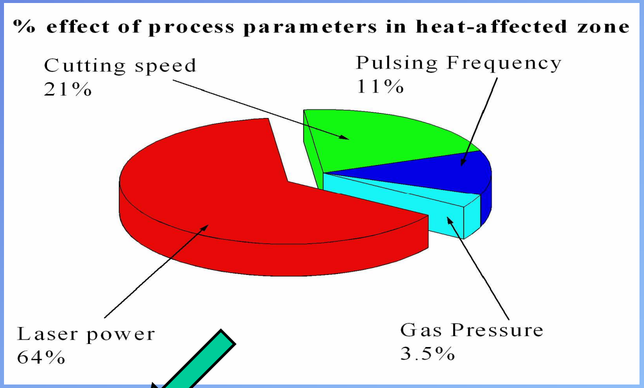
Laser cutting has a great number of applications in automotive, aerospace, shipbuilding and material processing industries and it is used for cutting a wide range of materials such as metals, ceramics, and composites regardless of their hardness or electrical conductivity.

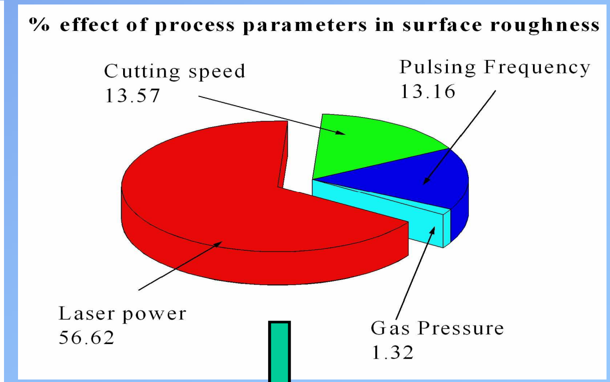


Good cutting quality is important, especially if parts are going to be used for assembly.

Statistical design of experiments and analysis can be used to identify the effects of the most important parameters on quality characteristics, such as kerf width, HAZ and cutting edge surface roughness.







Cutting speed and laser power have the strongest effect on the quality characteristics and especially on the kerf width and heat-affected zone.

Laser power, cutting speed and pulsing frequency are the major influencing parameters on cutting edge surface roughness.

REF: Stournaras A., P. Stavropoulos, G. Chryssolouris, (2006), “Investigation of Laser Cutting Quality of Aluminium”, In the Proceedings of International Congress on Applications of Lasers and Electro-optics, October 30-November 2, Scottsdale, Arizona, USA.

Innovative Manufacturing Processes

Laser Cutting

Regression analysis has been used for developing empirical models for the combined effect of laser power, cutting speed, pulsing frequency and assist gas pressure on laser cutting quality, i.e. Kerf width, cutting edge surface roughness and squareness.

First and second order main effects as well as interaction effects have been accounted for in the regression model, which has the general form:

$$Y_j = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + a_5 x_1^2 + a_6 x_2^2 + a_7 x_3^2 + a_8 x_4^2 + \\ + a_9 x_1 x_2 + a_{10} x_1 x_3 + a_{11} x_1 x_4 + a_{12} x_2 x_3 + a_{13} x_2 x_4 + a_{14} x_3 x_4$$

where Y_j, j=1,2,3 is the cutting quality parameter (Y_1: kerf width, Y_2: surface roughness, Y_3: squareness), x_1 is the laser power in watt, x_2 is the cutting speed in m/min, x_3 is the pulsing frequency in Hz and x_4 is the assist gas pressure in bar.

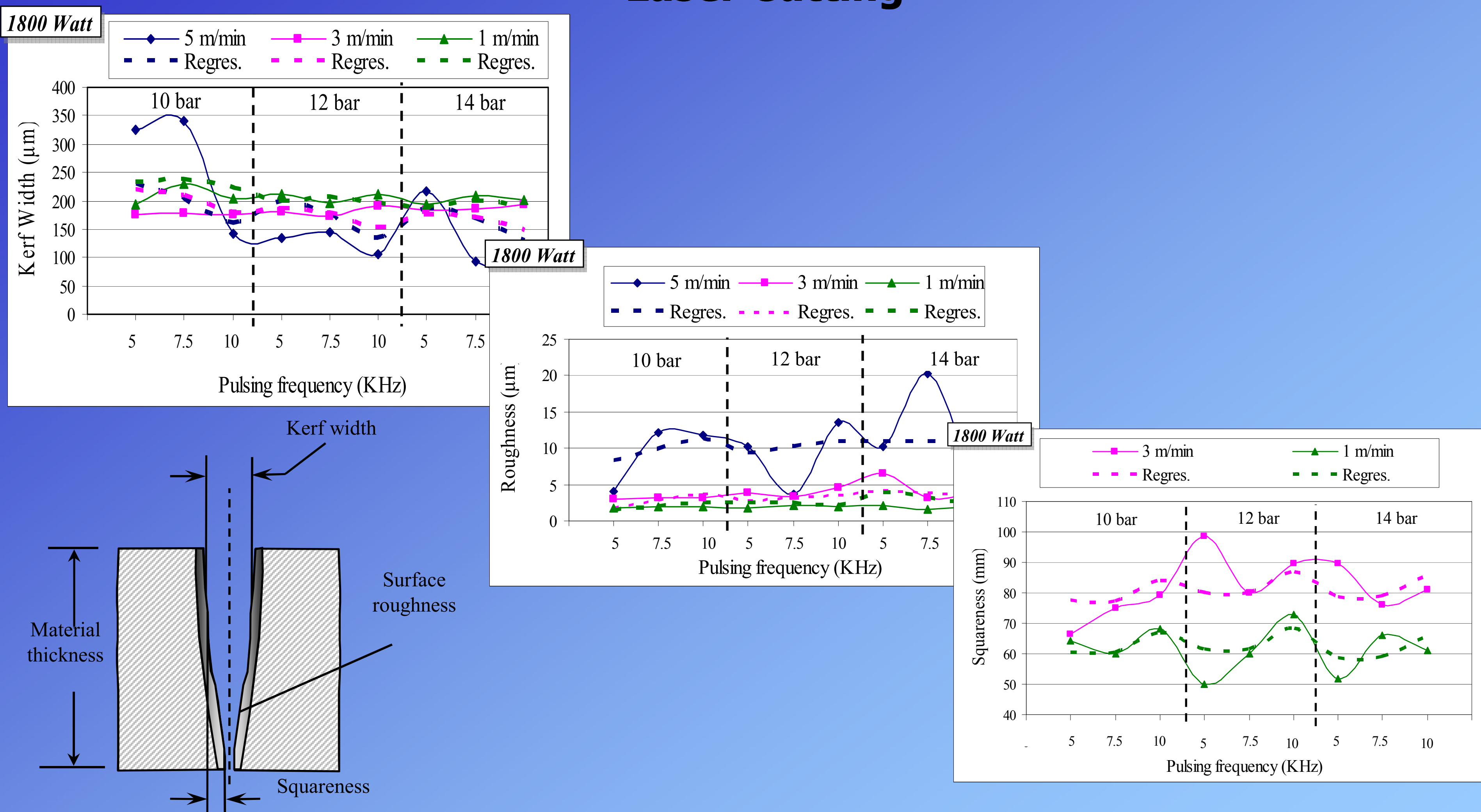
Coefficient	*Kerf width*	*Roughness*	*Squarenes*
a_0	504.34	106.25	376.99
a_1	0.46929	-0.14751	-0.48559
a_2	-52.827	8.4864	33.17
a_3	-0.029131	0.0018265	8.5473
a_4	-102.55	0.85838	-0.0036038
a_5	-0.00026054	4.9016e-005	0.0001573
a_6	3.1878	0.77448	-2.0805
a_7	-1.5565e-006	-9.4349e-009	-0.46552
a_8	2.7104	0.043294	5.2871e-007
a_9	0.0019046	-0.0058301	-0.0059667
a_{10}	2.3183e-005	1.0137e-007	0.0017512
a_{11}	0.022924	-0.00062169	-3.3974e-006
a_{12}	0.0029872	-9.1454e-005	-0.40466
a_{13}	0.00071328	-0.00014329	3.5441e-005
a_{14}	0	0	0
R^2	0.405	0.705	0.78

Regression model coefficients for cutting of Aluminium AA2024

REF: Salonitis, K., P. Stavropoulos, Stournaras A., G. Chryssolouris, (2007), “CO_2 Laser Cutting of Aluminium”, In the Proceedings of the 5th Laser Assisted Netshape Engineering, Erlangen, Germany, (September 2007), pp. 825-835.

Innovative Manufacturing Processes

Laser Cutting



Comparison of regression model results and experimental data for cutting of Aluminium AA2024

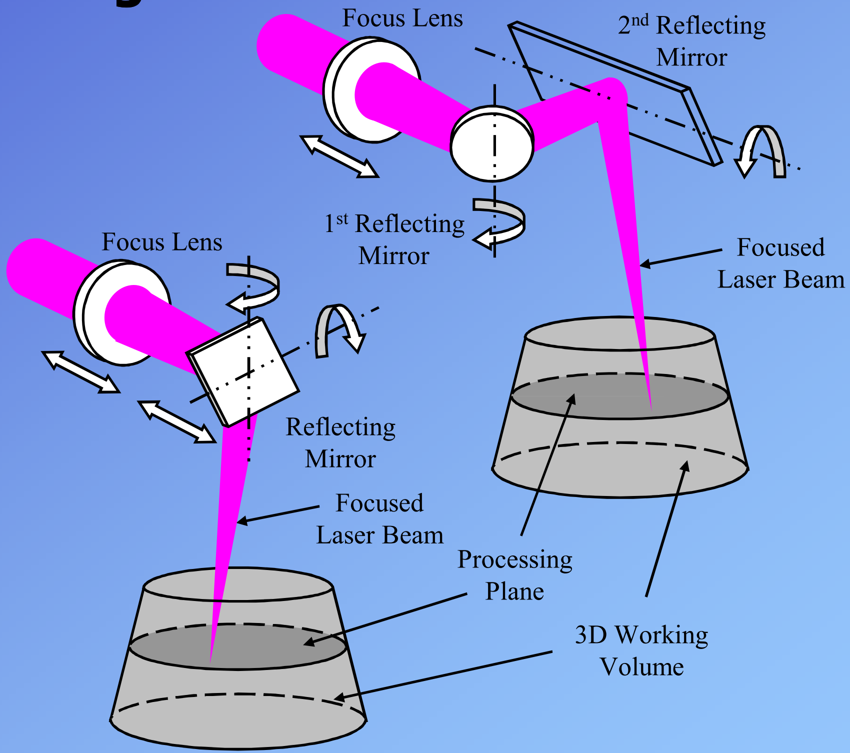
REF: Salonitis, K., P. Stavropoulos, Stournaras A., G. Chryssolouris, (2007), “CO_2 Laser Cutting of Aluminium”, In the Proceedings of the 5th Laser Assisted Netshape Engineering, Erlangen, Germany, (September 2007), pp. 825-835.

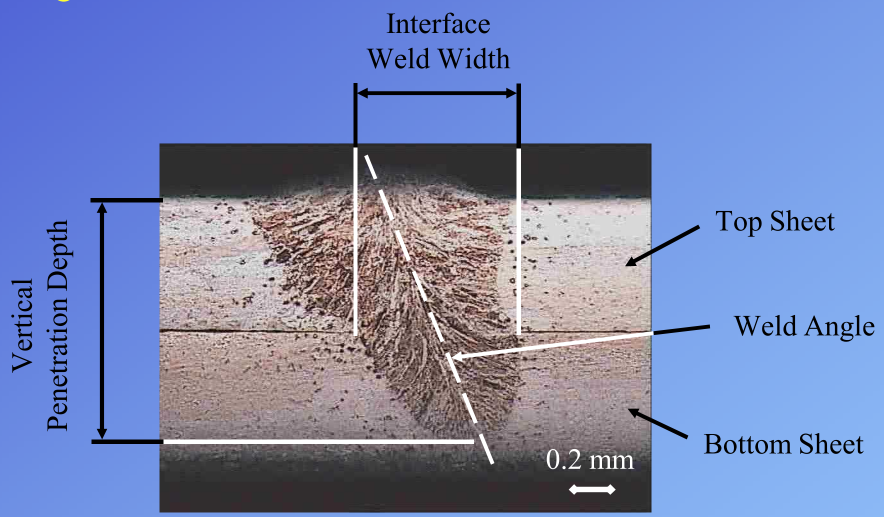
Innovative Manufacturing Processes

Remote Welding

Highly flexible and productive laser welding, used mainly in the automotive industry

The Remote Welding Systems (RWSs) implement:
- **High quality, high power laser sources**
- **Large focal lengths (up to 1.6 m)**
- **Scanning systems with low inertia deflecting optics (2-mirror or 1-mirror arrangements)**





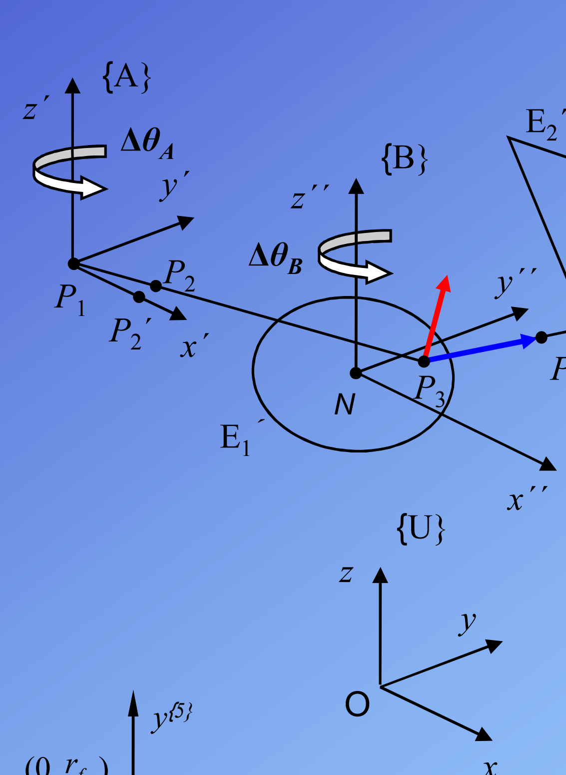
Characteristics:
- **Large Working Volumes (up to 2 m³)**
- **High laser moving speeds (up to 17 m/s)**
- **High production rates (typically 60 welds/min)**
- **Inclined welds are realised**

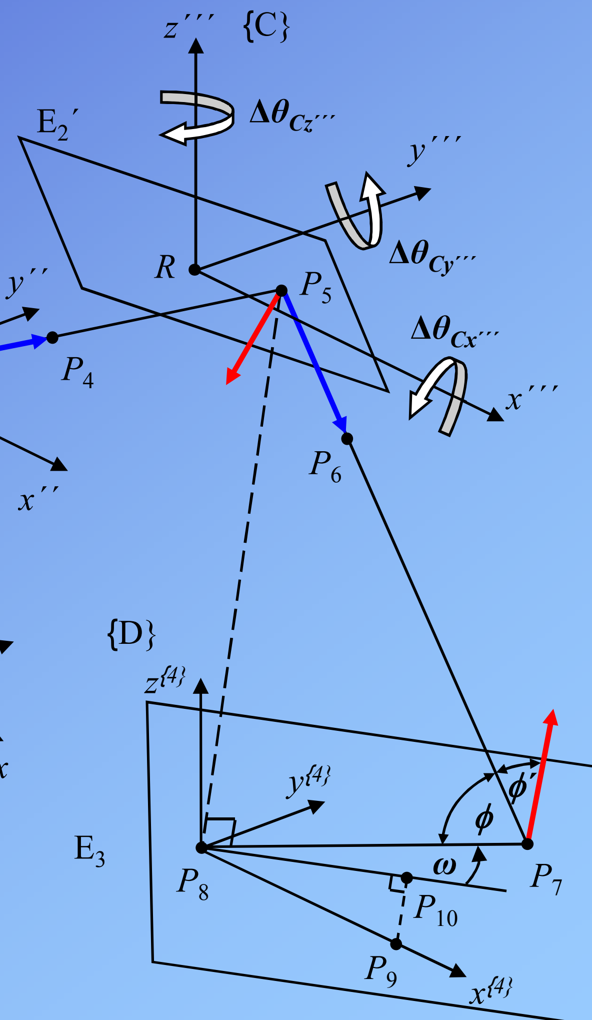
REF: Tsoukantas G., Salonitis K., Stournaras A., Stavropoulos P. and Chryssolouris G. (2006) "On Optimal Design Limitations of Generalized Two-Mirror Remote Beam Delivery Laser Systems: The case of remote Welding", *The International Journal of Advanced Manufacturing Technology*, DOI: 10.1007/s00170-005-0400-7.

Innovative Manufacturing Processes

Remote Welding Analysis

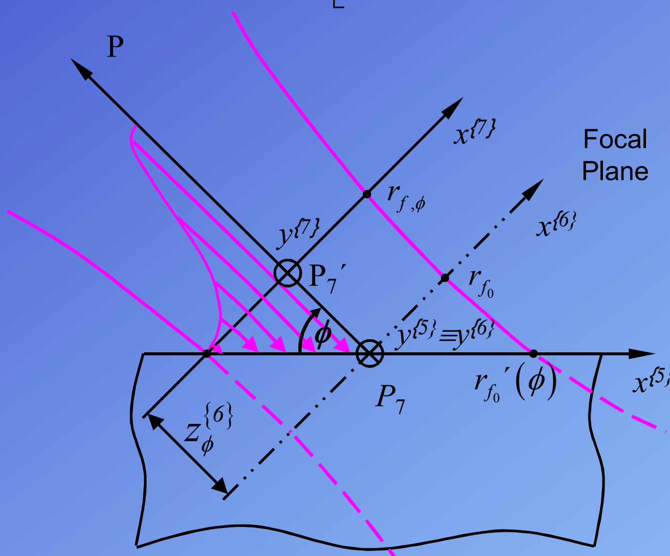
Geometrical Analysis of a generalized 2-mirror scanning system

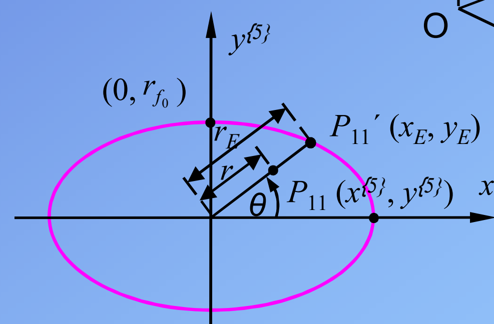




Calculation of the distorted Gaussian laser intensity distribution on an elliptical beam spot

$$I_E(r,\theta)=\frac{2P}{\pi r_{f_0}' r_{f_0}}\exp\left[\frac{-2r^2\left(r_{f_0}^{2}\cos^2\theta+r_{f_0}'^{2}\sin^2\theta\right)}{r_{f_0}'^{2} r_{f_0}^{2}}\right]$$



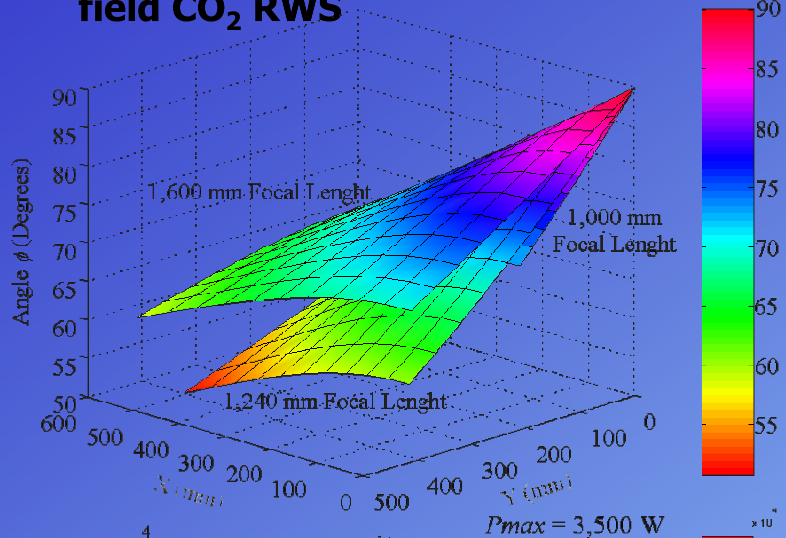


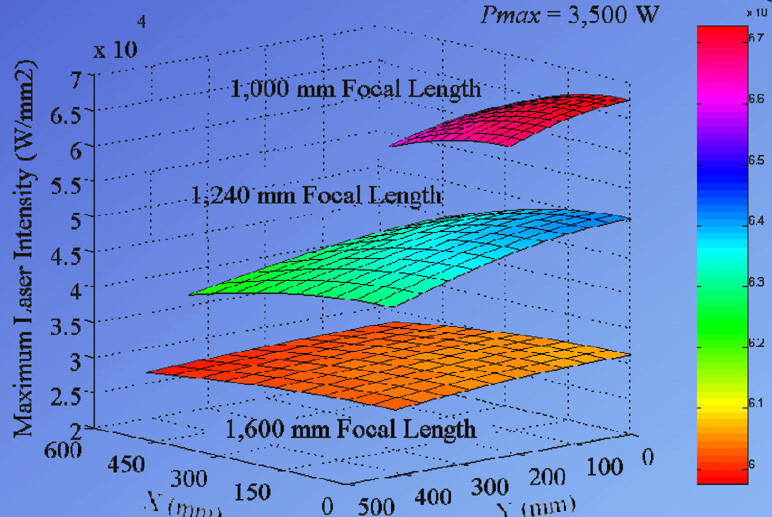
REF: Tsoukantas G., Salonitis K., Stournaras A., Stavropoulos P. and Chryssolouris G. (2006) “On Optimal Design Limitations of Generalized Two-Mirror Remote Beam Delivery Laser Systems: The case of remote Welding”, *The International Journal of Advanced Manufacturing Technology*, DOI: 10.1007/s00170-005-0400-7.

Innovative Manufacturing Processes

Remote Welding Limitations

Calculating the welding limitations on three different Focal Length options in a large field CO_2 RWS





Material	u (m/min)	$I_{keyhole}$ (10^4 W/mm^2)	Weld Depth at normal incidence (mm)	$\phi_{keyhole}$ (Degrees) Focal Length 1,000 mm	Focal Length 1,240 mm	Focal Length 1,600 mm
Mild Steel	7.5	2.1	0.8	18	25	42
DC04 ($FePO_4$) Steel	4	2.9	1	25	35	67
Zinc coated 600DP High-strength Steel	2	3.9	1.6	35	50	N/P
Mild Steel 1018	2	1.2	1	14	18	31
AISI 304 Stainless	5	4.0	1.2	37	53	N/P
12SR Stainless	1.3	1.5	2	13	17	29
Aluminium 1100	1	3.1	1	27	38	83
Aluminium 2017	1	2.7	1	24	32	60
Aluminium 2024	7.8	4.7	1	44	68	N/P
Aluminium 7N01	1	2.9	1	26	35	68
Aluminium 5083	1	2.3	1	20	27	47
Aluminium 5182	7.8	4.7	1	44	68	N/P
Aluminium 5000x	5	3.5	1	31	44	N/P
Aluminium 5754	4	2.8	1.5	25	34	64
Aluminium 6000x	5	2.0	1	17	23	40
Aluminium 6016	6	3.7	1	33	47	N/P
Aluminium 6082	7.8	4.7	1	44	68	N/P
Copper	5	5.2	1	51	N/P	N/P
Vanadium	7.5	3.2	1	28	39	N/P

REF: Tsoukantas G., Salonitis K., Stournaras A., Stavropoulos P. and Chryssolouris G (2006) "On Optimal Design Limitations of Generalized Two-Mirror Remote Beam Delivery Laser Systems: The case of remote Welding", *The International Journal of Advanced Manufacturing Technology*, DOI: 10.1007/s00170-005-0400-7.

Innovative Manufacturing Processes

Thermal Modelling of Laser Cladding

Theoretical Analysis – Laser Power effect

- **Fraction of the supplied powder that contribute to the clad formation**

$$\lambda = \frac{\dot{m}}{\dot{m}_f} = \frac{\dot{m}}{\rho_c \cdot u \cdot \left(V/l \right)}$$

$$\dot{m} = \dot{m}_{melted} + \dot{m}_{catch}$$

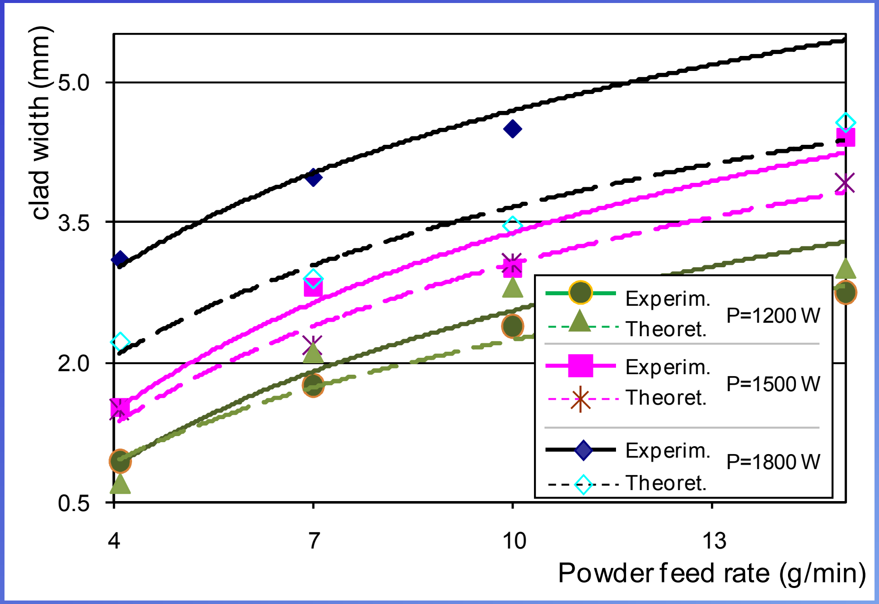
- **The mass of the solid particles that reaches the liquid substrate is considered negligible.**
- **The mass of the liquid particles can be determined from the energy consumed for the melting and the latent heat of fusion from the following equation:**

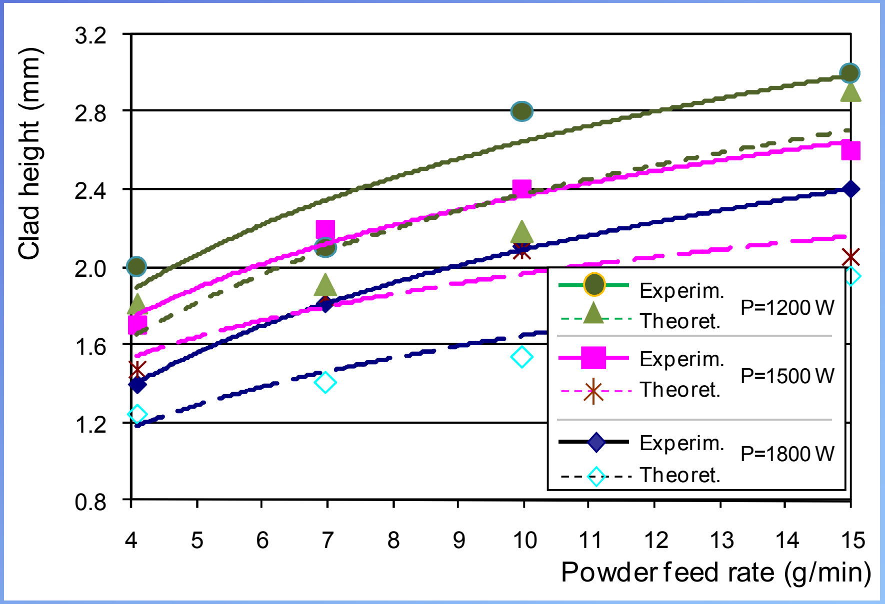
$$\dot{m}_{melted} = \frac{m_{melted}}{t} = \frac{Q_{particles}}{t \cdot L} = \frac{a \cdot Q_L}{t \cdot L} = \frac{a \cdot P}{L}$$

REF: Salonitis, K., P. Stavropoulos, A. Stournaras and G. Chryssolouris, "Thermal modelling of laser cladding process", Proceedings of the 5th Laser Assisted Net Shape Engineering, Erlangen, Germany, (September 2007), pp. 303-311

Innovative Manufacturing Processes

Thermal Modelling of Laser Cladding





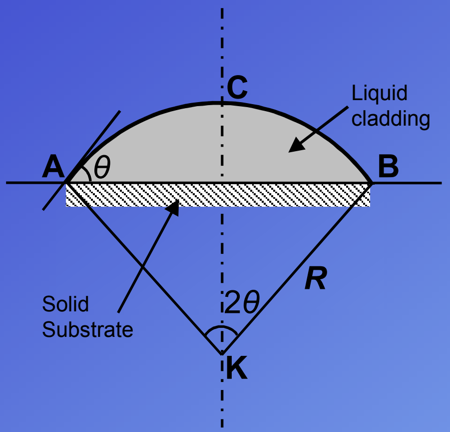
- **Increase of the laser power or the increase of the powder feed rate results in higher clad widths**
- **Increase of the laser power results in lower clad heights.**
- **Average deviation: 15 to 25% depending on the laser power**

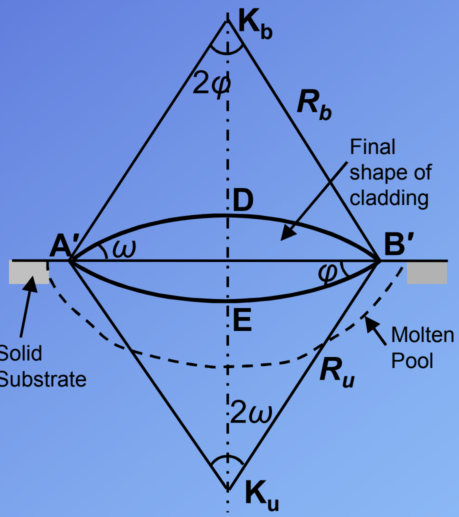
REF: Salonitis, K., P. Stavropoulos, A. Stournaras and G. Chryssolouris, "Thermal modelling of laser cladding process", Proceedings of the 5th Laser Assisted Net Shape Engineering, Erlangen, Germany, (September 2007), pp. 303-311

Innovative Manufacturing Processes

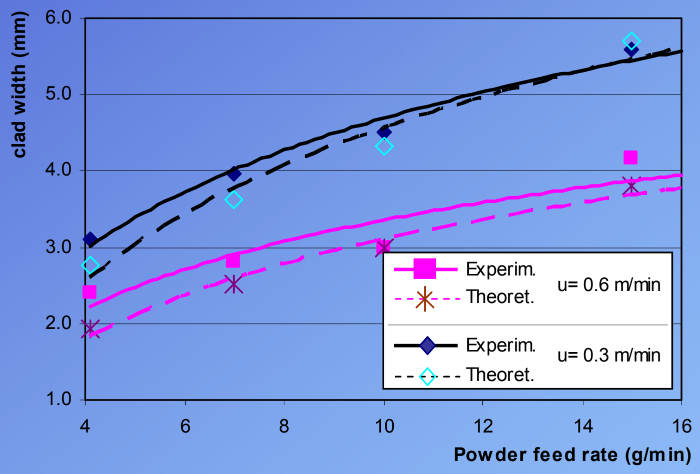
Analytical Modelling of Laser Cladding

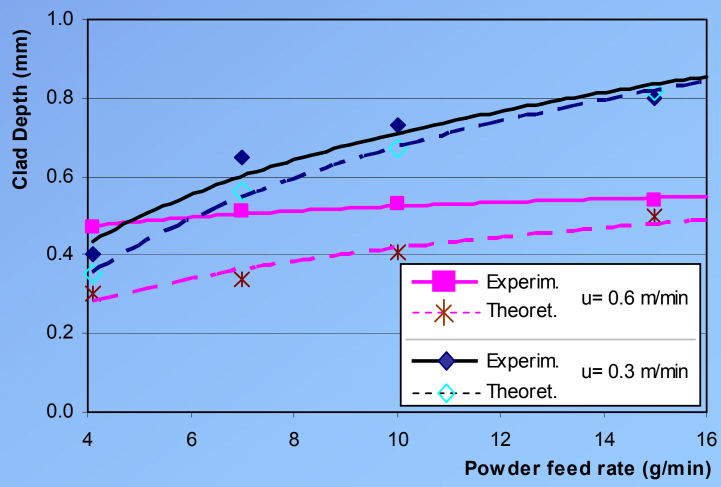
Two step approach:





Estimation of the clad geometry (width, depth, height):



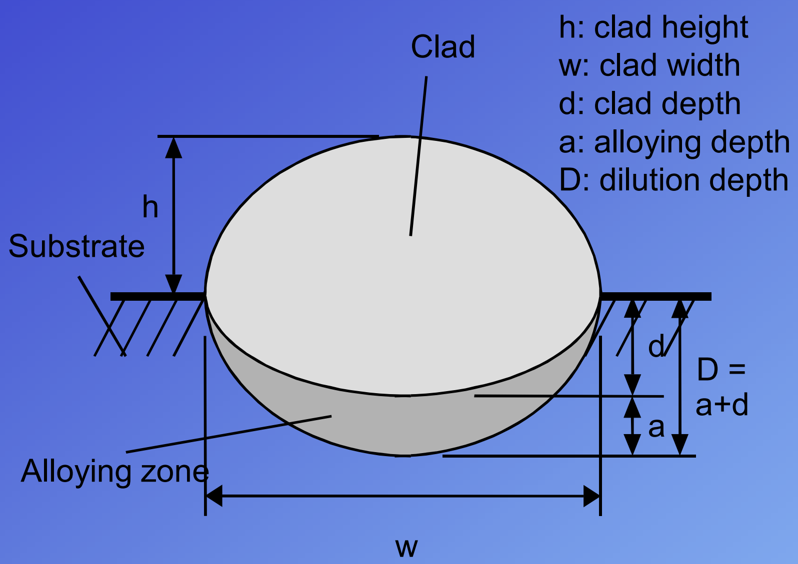


REF: Lalas C., Tsirbas K., Salonitis K. and Chryssolouris G. (2006) "An analytical model of laser clad geometry", *International Journal of Advanced Manufacturing Technology*, DOI 10.1007/s00170-005-0318-0.

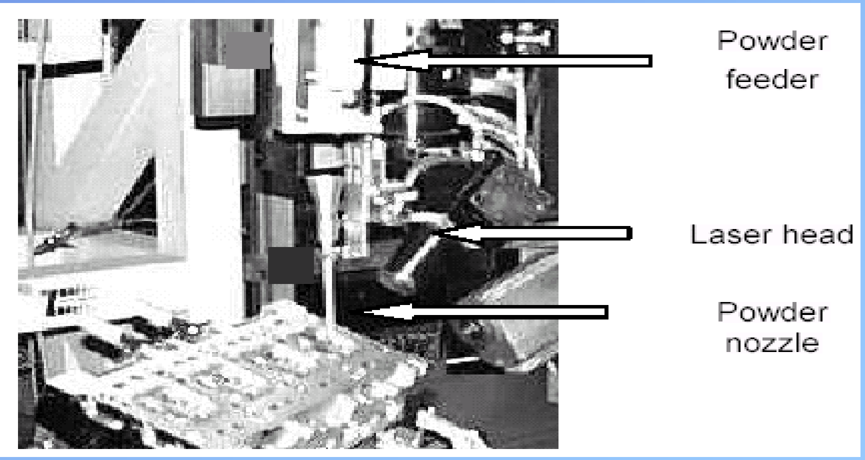
Innovative Manufacturing Processes

Laser Cladding - Experimentation

Clad geometry includes two main regions, namely the clad and the alloying zone. Clad height (h), width (w) and depth (d) define the final geometry of the clad after the end of the process. In the alloying zone the added material and the molten substrate are mixed. The sum of the alloying zone thickness (a) and the clad depth (d) define the clad dilution (D).



Clad Characteristics

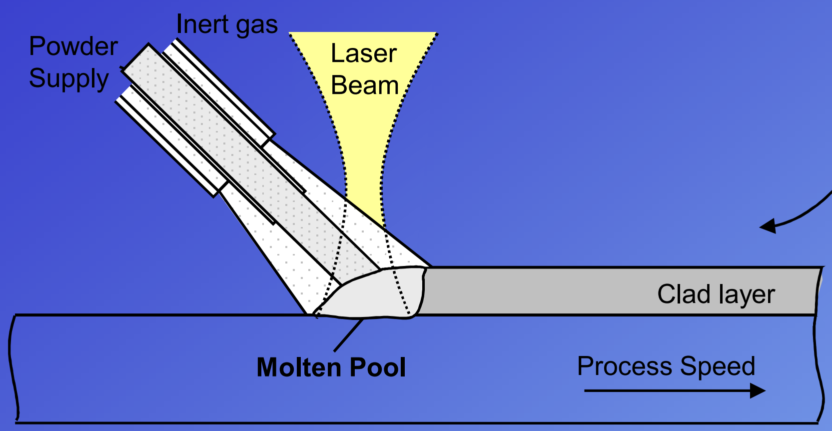


Experimental layout for Laser Cladding

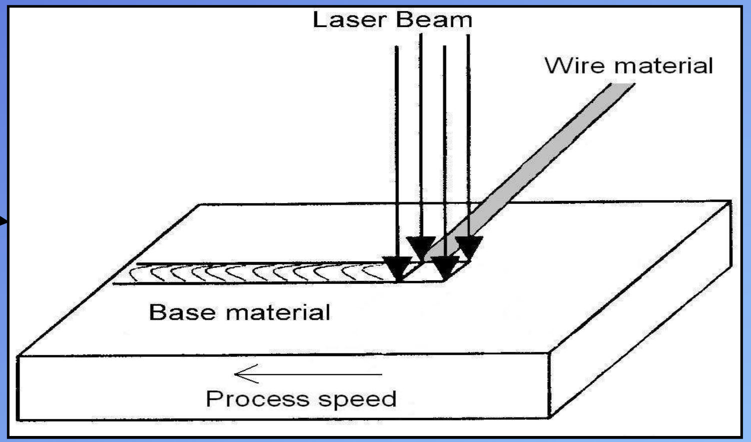
REF: Chryssolouris G., Zannis S., Tsirbas K. and Lalas C. (2002) “An Experimental Investigation of Laser Cladding”, *CIRP Annals*, Vol. 51 No1, pp. 145-148.

Innovative Manufacturing Processes

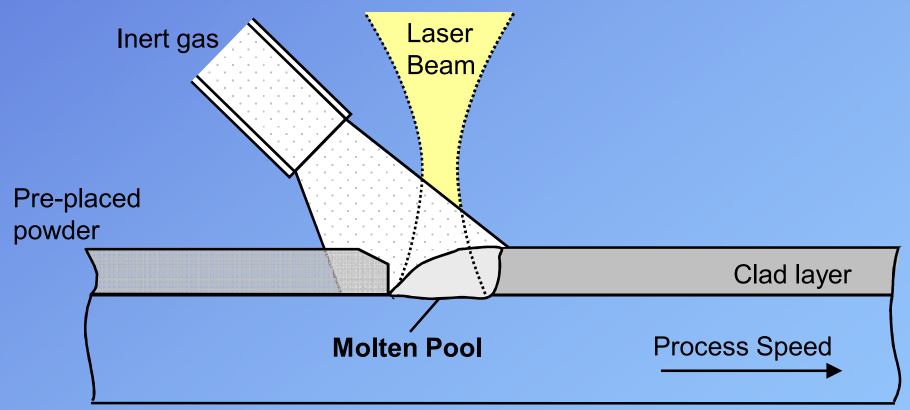
Basic Laser Cladding Techniques



Schematic of the powder blown laser cladding process.



Schematic of the wire feeding laser cladding process.



Schematic of the pre-placed powder laser cladding process.

REF: Chryssolouris G., Zannis S., Tsirbas K. and Lalas C. (2001) "On Laser Cladding", *The 34th CIRP International Seminar on Manufacturing Systems*, 16-18 May 2001, Athens, Greece.

Innovative Manufacturing Processes

Investigation of Pulsed Laser Grooving Process

- **Each pulse results in heating (t_{on}) and cooling (t_{off}) of the work piece surface.**

- **Heat transfer within the work piece material:**

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a}\frac{\partial T}{\partial t}$$

a: Thermal diffusivity

- **Initial & Boundary conditions:**

Heating

$$T_i(z,x,0) = T'_{i-1}$$

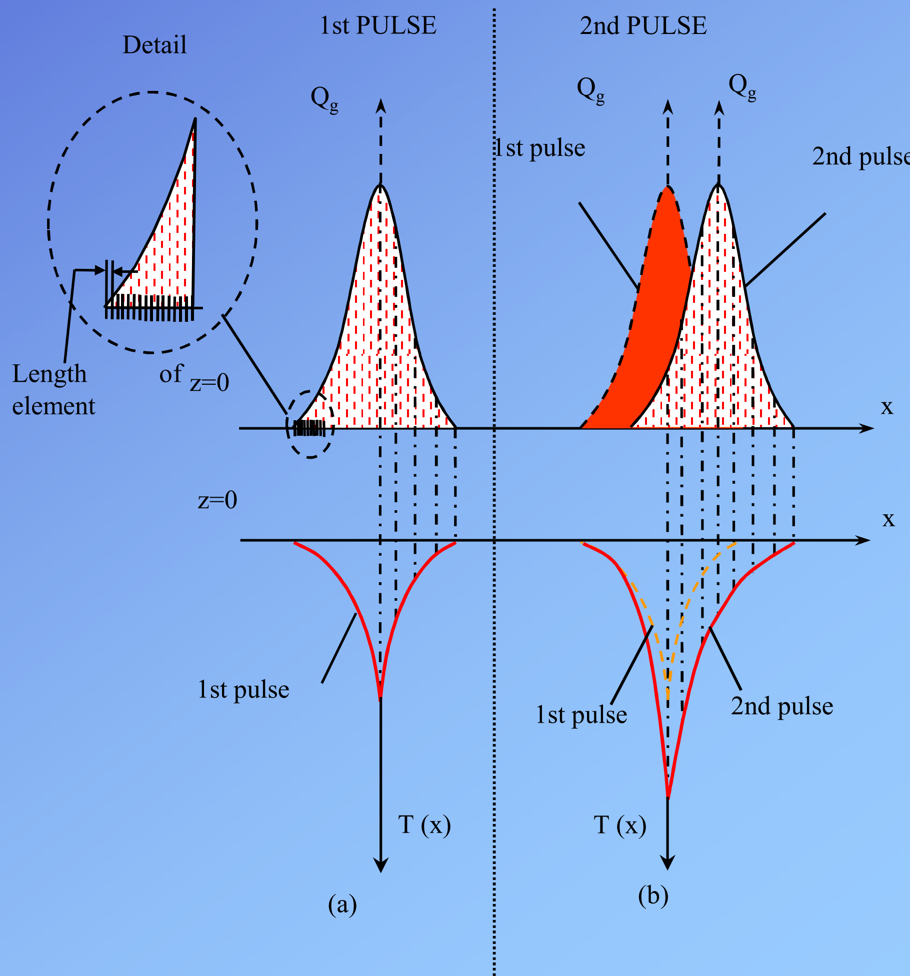
$$-k\left.\frac{\partial T_i}{\partial z}\right|_{z=0} = Q_g \quad \text{for } -R_{f0} \le x \le R_{f0}$$

$$h(T_0 - T')_{Z=0} = -k\left.\frac{\partial T'}{\partial Z}\right|_{Z=0} \quad \text{for } x \le -R_{f0} \text{ or } x \ge R_{f0}$$

Cooling

$$T_i'(z=0, x, t=0) = T_i$$

$$h(T_0 - T')_{Z=0} = -k\left.\frac{\partial T'}{\partial Z}\right|_{Z=0}$$



REF: Stournaras A., P. Stavropoulos, G. Chryssolouris, (2006), “Theoretical and Experimental Investigation of Pulsed Laser Grooving Process”, In the Proceedings of International Congress on Applications of Lasers and Electro-optics, October 30-November 2, Scottsdale, Arizona, USA.

Innovative Manufacturing Processes

Investigation of Pulsed Laser Grooving Process

- **Energy balance of the melt pool:**

$$\boxed{Q_{in} = Q_L + Q_{Cond} + Q_{Conv}}$$

***Q_{in}*: the energy that enters the work piece**
***Q_L*: the energy required for material's phase change**
***Q_{Cond}*: the heat conducted in the work piece**
***Q_{Conv}*: the heat lost in the air through convection**

$$Q_{in} = \int_{x1_n}^{x2_n} Q_g \, dx \cdot b \cdot t_p$$

$$Q_L = m_i * L = V_i * \rho * L$$

$$Q_{Cond} = \left(k * A_{Cond} * \frac{\partial T}{\partial n}\right) * t_p = \left(k * A_{Cond} * \frac{\Delta T}{\Delta s}\right) * t_p$$

$$Q_{Conv} = \left(h * A_{Conv} * \Delta T\right) * t_p$$

By calculating the volume *Vi* of the melted material at each pulse, the depth *zi* can be calculated

$$Z_i = \frac{Q_{in} - k \cdot t_p \cdot A_i \dfrac{\Delta T}{\Delta S} - h \cdot A_i \cdot t_p \cdot \Delta T}{A_i \cdot \rho \cdot L + 2 \cdot k \cdot \pi \cdot r_i \dfrac{\Delta T}{\Delta S} \cdot t_p}$$

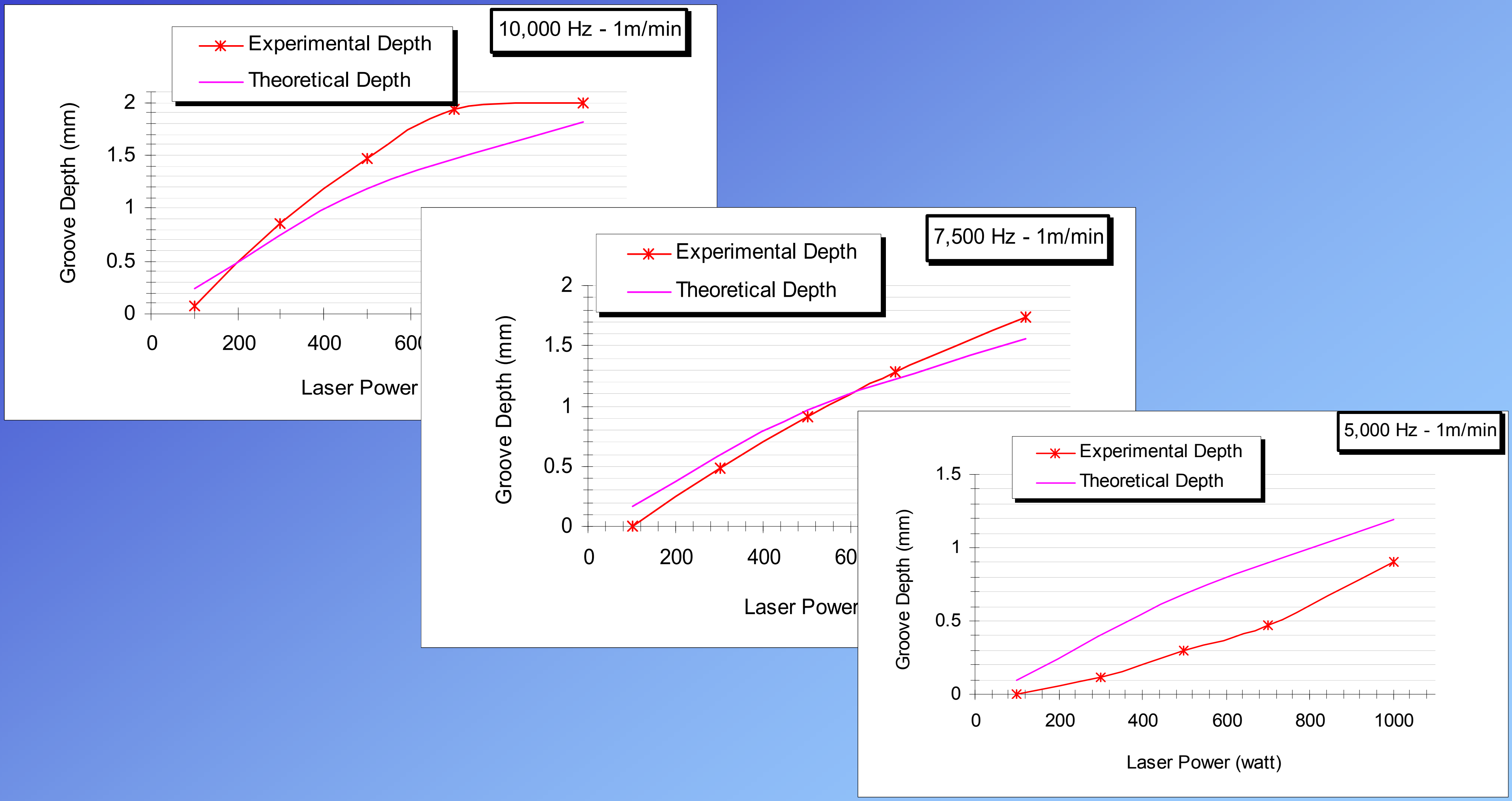
A_i: Surface area of the melted finite volume
r_i: Radius of the cylindrical finite volume
ρ: Density of the material
t_p: Pulse duration

REF: Stournaras A., P. Stavropoulos, G. Chryssolouris, (2006), "Theoretical and Experimental Investigation of Pulsed Laser Grooving Process", In the Proceedings of International Congress on Applications of Lasers and Electro-optics, October 30-November 2, Scottsdale, Arizona, USA.

Innovative Manufacturing Processes

Investigation of Pulsed Laser Grooving Process

Theoretical and Experimental results:



REF: Stournaras A., P. Stavropoulos, G. Chryssolouris, (2006), “Theoretical and Experimental Investigation of Pulsed Laser Grooving Process”, In the Proceedings of International Congress on Applications of Lasers and Electro-optics, October 30-November 2, Scottsdale, Arizona, USA.

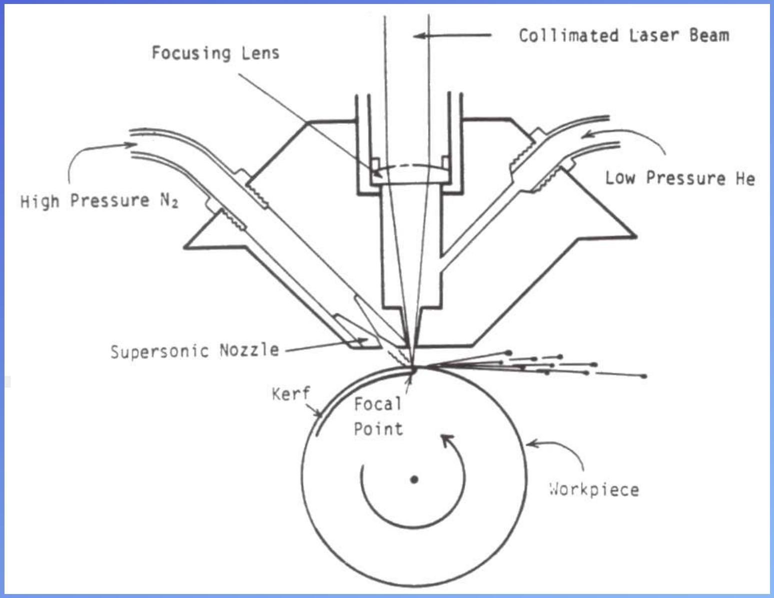
Innovative Manufacturing Processes

Laser Grooving of Ceramics and Composites

Experimental Setup

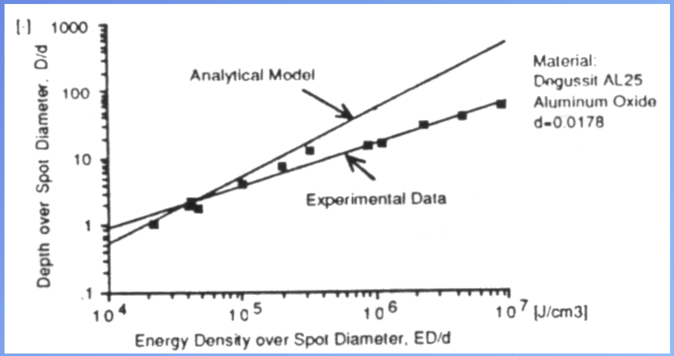
Laser turning in radial and longitudinal blind cuts

Utilization of Off-axial gas jet

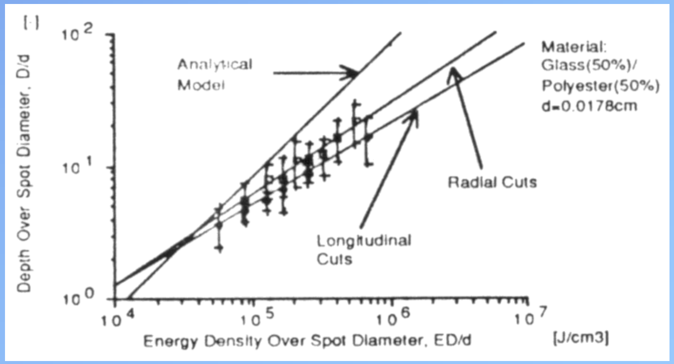


Experimental Data

Ceramic Material: Al_2O_3



Composite Material: Glass/Polyester



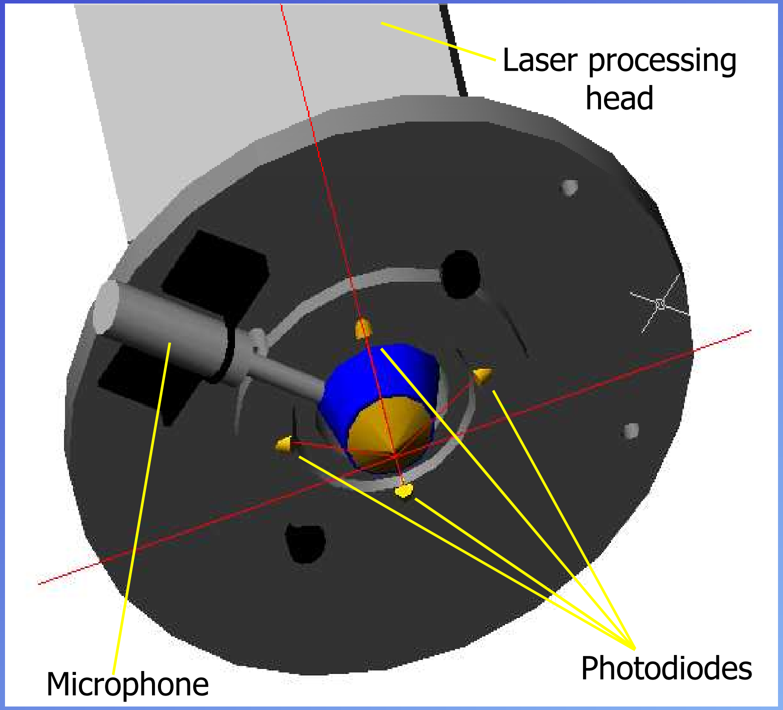
REF: Chryssolouris G., Sheng P. and Choi W.C. (1989) "Investigation of the Laser Grooving Process for Ceramic and Composite Materials", *Proc. of the 15th Conference on Production Research and Technology*, NSF, SME, University of California at Berkeley, pp. 617-622.

Innovative Manufacturing Processes

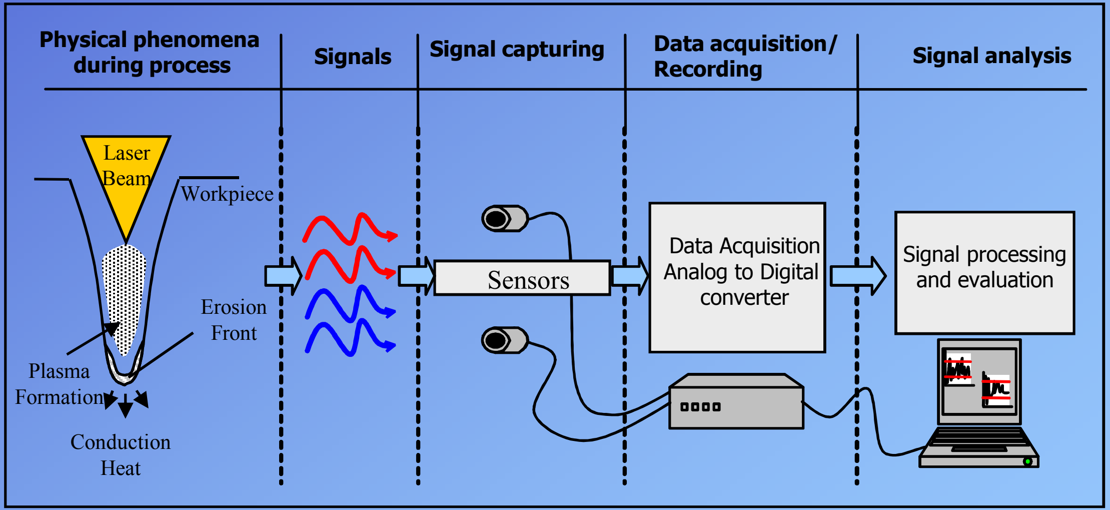
Laser Process Monitoring

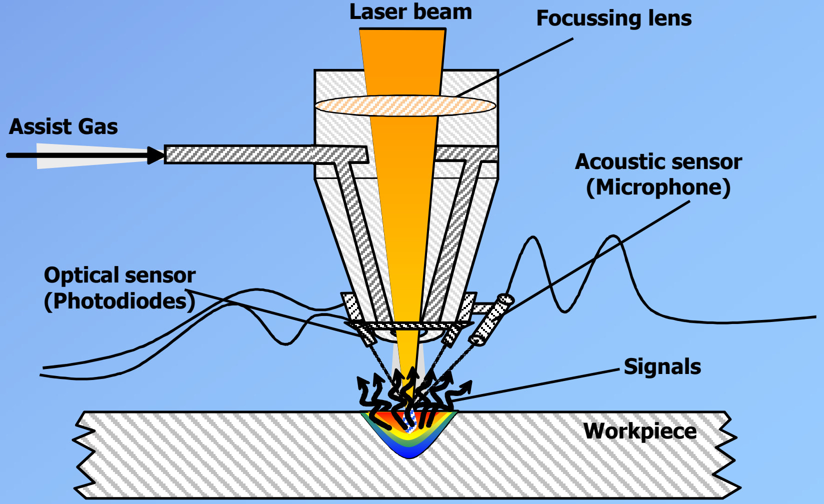
Pulsed Laser Drilling process monitoring using optical and acoustical means

Process information can be obtained by measuring and characterizing the various forms of energy that propagates from the laser material interaction site. Electromagnetic radiation and acoustic waves are two of the most significant signals that can be used for extracting information regarding process' evolution and characteristics.



Off-axial sensor arrangement

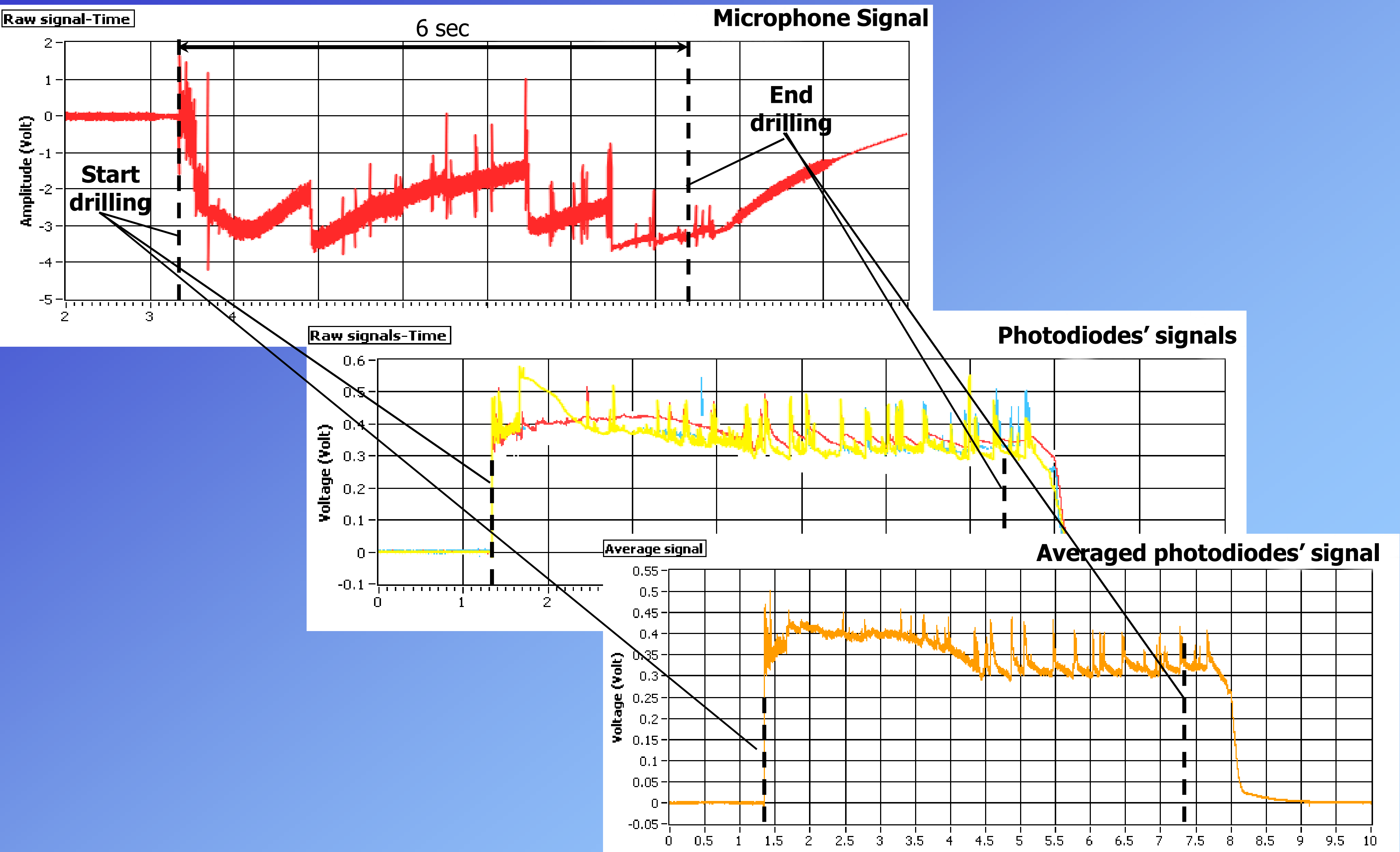




Innovative Manufacturing Processes

Laser Process Monitoring

Pulsed Laser Drilling process monitoring using optical and acoustical means

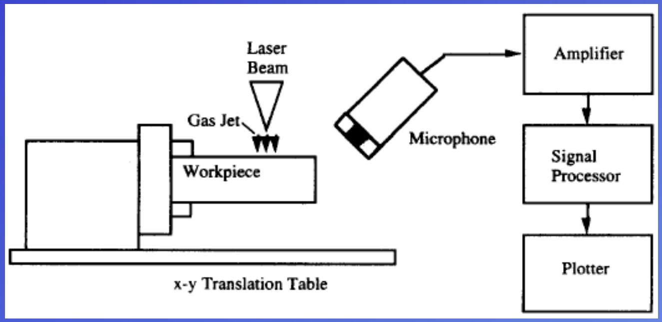


Innovative Manufacturing Processes

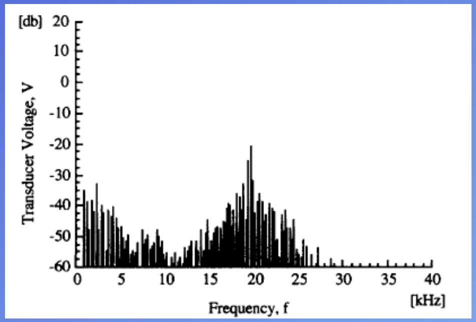
Laser Process Monitoring

Sensing of Laser Drilling and Grooving/Cutting

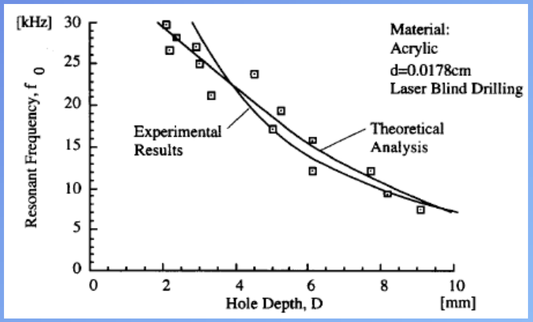
Experimental Setup



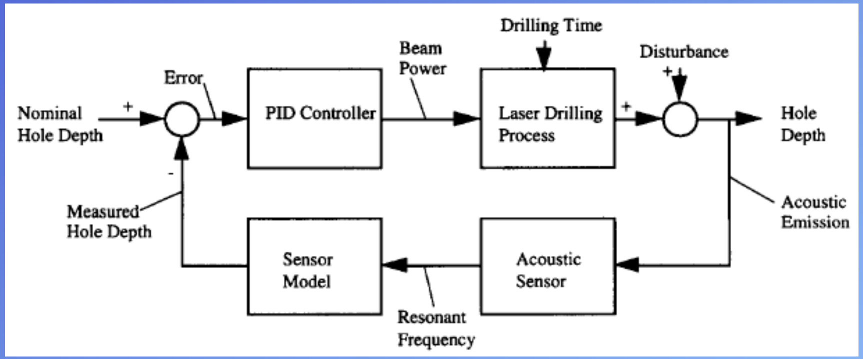
Signal Elaboration



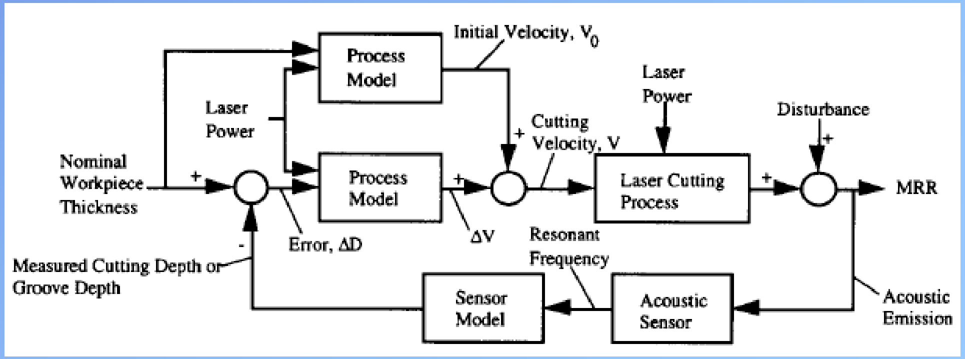
Utilization of Theoretical Model



Closed Loop Control Scheme for Laser Drilling



Closed Loop Control Scheme for Laser Grooving/Cutting

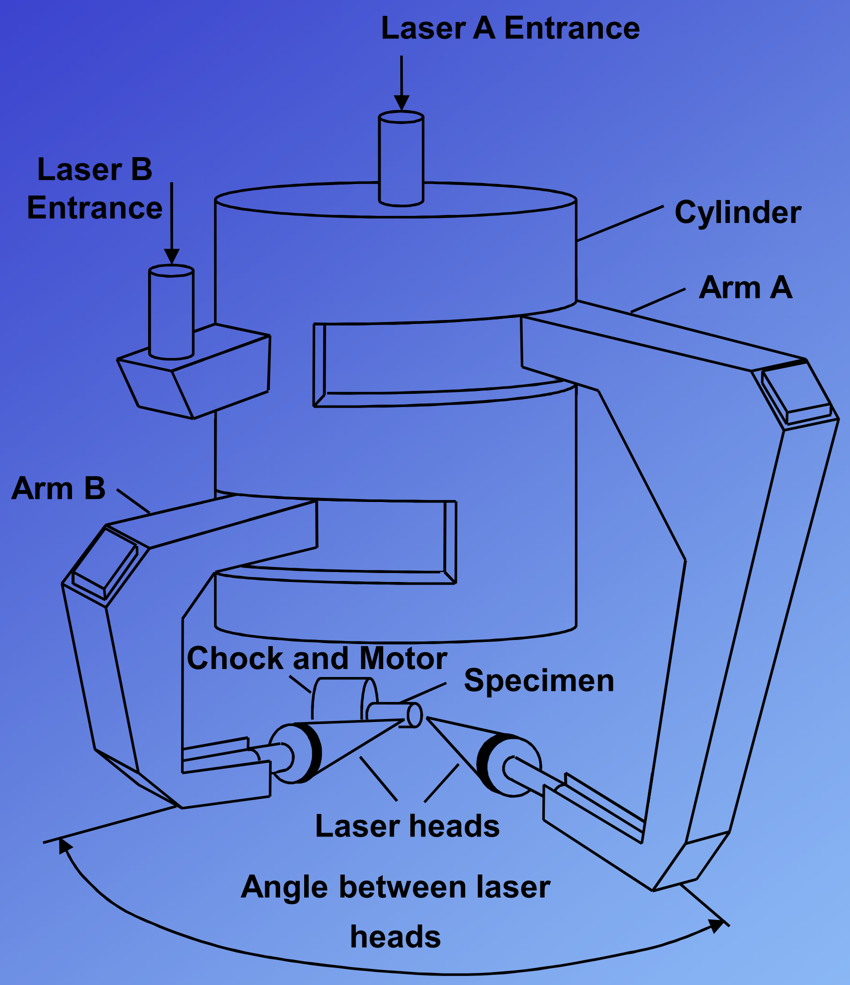


REF: Sheng P. and Chryssolouris G. (1994) "Investigation of acoustic sensing for laser machining processes Part 1: Laser drilling", *Journal of Materials Processing Technology*, Vol. 43, Issues 2-4, pp. 125-144.

Sheng P. and Chryssolouris G. (1994) "Investigation of acoustic sensing for laser machining processes Part 2: Laser grooving and cutting", *Journal of Materials Processing Technology*, Vol. 43, Issues 2-4, pp. 145-163.

Innovative Manufacturing Processes

3D Laser Materials Processing



ADJUSTMENT OF SPECIMEN AND ARMS POSITION

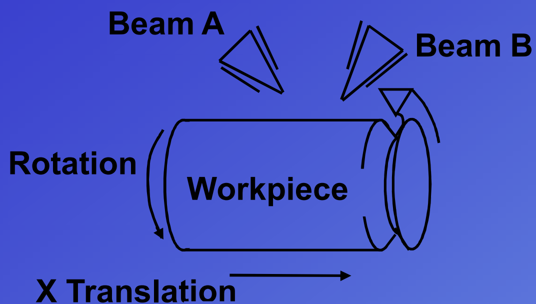
The concept of this device allows the entrance of two different Laser beams and their guidance to the moving heads through arms A and B.

By adjusting the angle position of the heads, in combination with the rotating specimen, different geometries can be created.

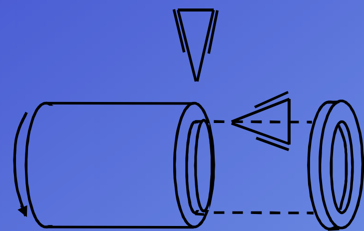
REF: Chryssolouris G., Sheng P. and Anastasia N. (1991) "Development of Techniques for Three-Dimensional Laser Machining" SAE 1991 Transactions, Vol. 100/Journal of Materials and Manufacturing/Section 5, pp. 916-924.

Innovative Manufacturing Processes

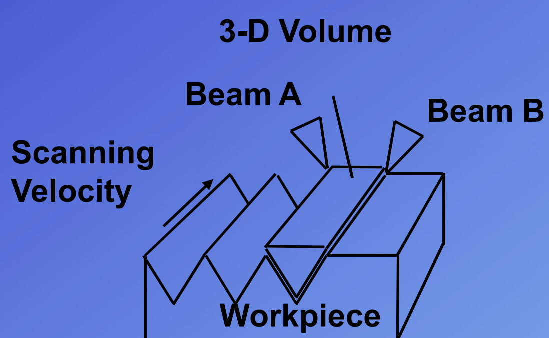
3D Laser Materials Processing



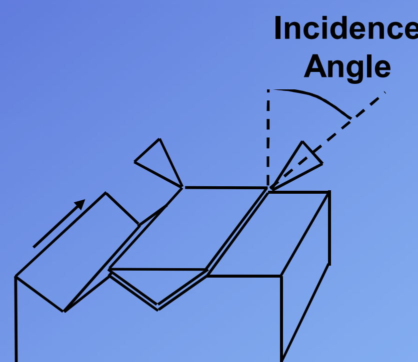
(a) Helix Removal



(b) Ring Removal



(c) Laser Milling With Small Incidence Angle



(d) Laser Milling With Large Incidence Angle

3D LASER MACHINING USING TWO CONVERGING LASER BEAMS

This concept utilizes two intersecting beams in order to produce parts with shapes similar to those produced by conventional methods

Turning operations can be accomplished by helix/ring removal [Fig. a, b]

For the case of laser milling, two laser beams are positioned at oblique angles from the workpiece surface to create converging grooves in a workpiece. [Fig. c, d]

REF: Chryssolouris G., Sheng P. and Anastasia N. (1991) "Development of Techniques for Three-Dimensional Laser Machining" *SAE 1991 Transactions*, Vol. 100/Journal of Materials and Manufacturing/Section 5, pp. 916-924.

Tsoukantas G., Salonitis K., Stavropoulos P. and Chryssolouris G. (2002) "An Overview of 3D Laser Materials", *Processing*, *Proceedings of 3rd International Conference on Laser Technologies and Applications*, Patras, Greece, 2002, pp. 224-228.