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Characterization of laser-material interaction during laser cladding process

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ABSTRACT

The interaction between a gas-powder mixture and a laser beam has been studied in the conditions of laser surface cladding. A powder is blown with an inert gas, coaxially with a laser beam, through a nozzle. A substrate, placed underneath, receives part of the laser beam and the heated powder material. A surface layer of the blown material is formed on the substrate. The paper describes the interaction between the laser beam and the gas-powder mixture. Signals that have been recorded, include : laser power transmitted by the powder stream, spatial extension of the plasma, temporal variations and spectral content of light emitted by the ionized mixture.

INTRODUCTION

Laser cladding is one of the numerous techniques of surface treatment [1] which allows us to modify a material surface according to specifications required for a given application. Using a laser beam to clad a material on a substrate has several advantages : a well localized heating source, a low dilution of the cladding metal with the substrate material, a low distortion of the substrate material, a cladded layer with a fine microstructure, the possible integration into a robotic system. Laser cladding has been successfully applied to various materials using lateral powder deposition : Stellite/mild steel, Chromium/Titanium, Nickel/mild steel, stainless steel/mild steel. There are several techniques which can be used to feed the material mixture on a surface to be clad. Preplacing a powder layer on the substrate is the simplest one. However, in this case, the powder tends to move around while it is melted by the laser beam. Blowing the powder with an inert gas into the laser-generated melt pool on the substrate has several advantages [2] : a controlled level of dilution, localized heating and, hence, a small heat affected zone, a good fusion bonding, a smooth surface finish. Blowing can be done laterally, at an angle above the surface. Although such a geometry gives satisfactory results in most cases, a feeding of the powder, coaxially to the laser beam, should give a better flexibility and make the process independent of the direction of motion of the substrate. Therefore, a coaxial nozzle can be expected to be more efficient for cladding surfaces with complex shapes. Another advantage of coaxial feeding of the powder material is that it ensures a controlled heating of the powder by the laser beam. Fusion and vaporization occur. Sometimes avalanche ionization leading to a plasma is observed; this plasma can impede the process and its effects need to be well defined.

Coaxial powder distribution has been successfully applied by several authors [3]. However the interaction between a flowing gas-powder mixture, coaxially irradiated by a high power laser beam is rather complex due to the many physical phenomena that are taking place simultaneously and the numerous parameters which may affect the energy balance. Good results can be obtained by an empirical adjustment of the parameters but, as far as we know, no attempt has been made to define the optimal parameters of the cladding process through a systematic observation of the signals emitted in the interaction volume. We have recorded some of these signals which bring some hints on the energy redistribution between the gas, the powder, the environment and the substrate.

THE GAS-POWDER-LASER BEAM DISTRIBUTION SYSTEM

The distribution nozzle is shown on Figure 1. It consists of two coaxial conic parts. A transport gas (argon or helium) is used to blow the powder through the inner space between the two cones, and from there, through the circular exit toward the substrate surface, along the axis of the laser beam. The inner cone is provided with an entrance and a passage for a stream of gas which creates an excess pressure in the inside chamber, preventing the flowing of a fraction of the powder up, toward the focusing laser spot where it could be ionized. Moreover, this gas jet insures an optimum confinement of the powder stream along the laser beam axis. The cooling water flowing around the tip of the nozzle is aimed to remove the heat due to absorption of the reflected beam from the substrate during the cladding process.

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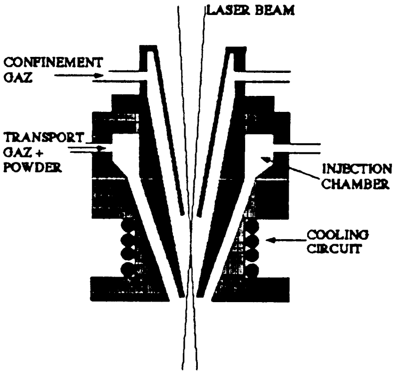

Fig. 1 : Sketch of a nozzle for coaxial distribution of powder and laser beam.

Figure 2 displays a macrograph of a single track of Stellite cladded on a mild steel. The track has a thickness of 3,2 mm. No porosity is visible. The interface between the deposited material and the substrate is well defined, showing a low dilution. The heat affected zone extends to less than half a millimeter in the substrate.

Fig. 2 : Macrograph of single track of Stellite on mild steel. Track thickness : 3,2 mm.

Efficiency of the cladding process using the above described nozzle is excellent. Up to 80 % of the powder is effectively used as it can be seen from Figure 3. The sample can be located from 9 to 12 mm below the nozzle tip without efficiency change.

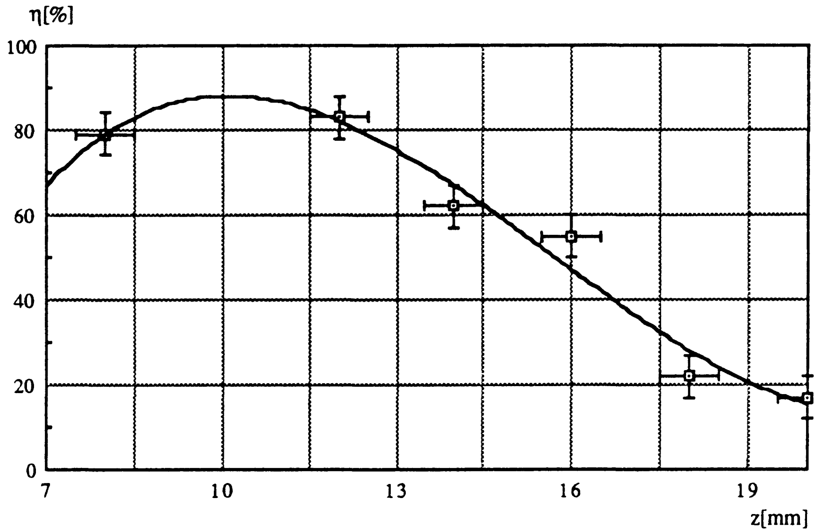

Fig. 3 : Efficiency of powder deposition vs distance between nozzle and sample for Stellite.

PHYSICAL PHENOMENA TAKING PLACE IN THE GAS-POWDER MIXTURE IRRADIATED BY THE HIGH POWER LASER BEAM

The interaction between a high power laser beam and a flowing gas-powder mixture involves a number of physical phenomena : scattering, absorption of radiation which leads to rapid heating followed by fusion, vaporization and ionization of the powder particles. The first difficulty of the analysis arises from the inhomogeneous distribution of the powder and laser beam. We have used a fast axial flow, RF excited CO_2 laser, with a maximum output power of 5 kW. In the range of 3 to 5 kW, the beam is multimode with a spatial profile shown on Figure 4.

The powder density profiles at different distances from the nozzle exit are shown on Figure 5. The image on the left side of the figure has been obtained by scanning the powder stream with a visible laser beam. The characterization has first been made without the sample to be clad. Three zones can be distinguished in the interaction volume along the vertical axis. In the first zone, located immediately beneath the nozzle exit, the powder stream still has the conical shape of the injection system. In this zone the powder progressively enters the space occupied by the laser beam. Heating of the powder is moderate but some loss of laser energy already occurs as it will be seen on the transmission curve, due to absorption and scattering of the radiation by the cold particles.

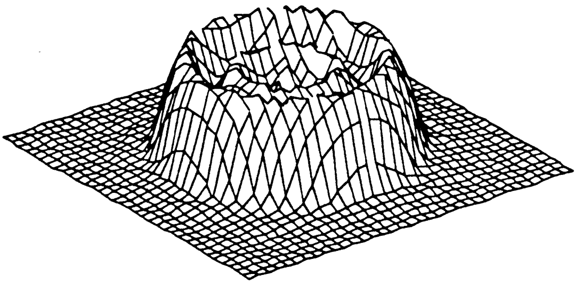

Fig. 4 : Intensity profile of the laser beam used in this work. Power range : 3 to 5 kW.

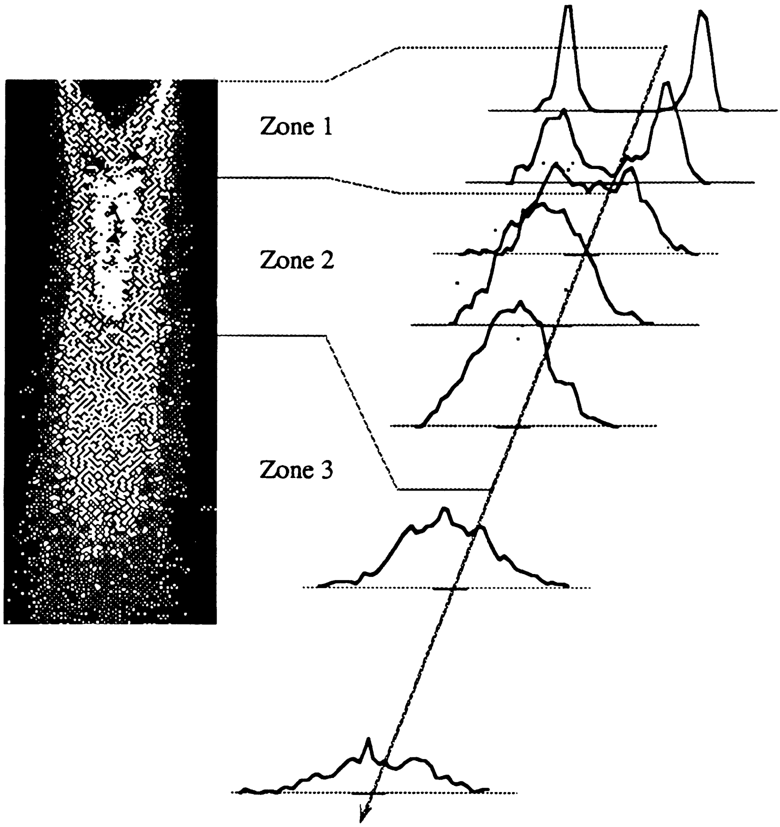

Fig. 5 : Density profile of the powder stream at different distances from the nozzle exit.

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The second zone has a cylindrical shape. In this zone, powder confinement is optimum and there is a good superposition of the powder stream and the laser beam. Absorption of the laser beam by the powder is expected to be high in zone 2. Fusion and vaporization take place. Excessive heating due to long interaction time or/and high laser power results in plasma formation as it will be described next.

Below the bright spot that we identified as zone 2, there is a third zone where the powder is no more confined along the axis. This zone is expected to be of little use for the cladding process. Obviously the best results should be obtained for a sample placed in zone 2. The introduction of a substrate alters the interaction conditions : part of the laser beam will be reflected by the surface. The melted layer will also radiate some energy up to the incoming powder.

EXPERIMENTAL SET-UP AND OBSERVATIONS

The experimental set-up is shown on Figure 6. The following detectors have been used : a calorimeter to measure the laser power transmitted by the powder and reaching the sample, a Silicon photodiode to record the temporal variations of the photonic signal emitted by the heated powder, a spectrograph to record the spectrum of the signal, a monoshot CCD camera to visualize the spatial extension of the plasma appearing at high laser power.

Calorimeter measurements

During laser cladding with coaxial feeding of powder, only a part of the laser energy is transmitted through the powder. The energy that does not reach the substrate surface is partly reflected, partly scattered and partly absorbed by the powder particles. It would not be easy to evaluate precisely the different terms but measurement of the transmitted part is possible. For doing this, the powder stream has been deflected by a high pressure gas at various distances from the nozzle exit; the geometry of the deflecting gas jet is optimized to introduce negligible distortion on the powder stream above it.

At low power (below 3 kW) the transmission decreases exponentially over the whole length of the powder stream. The lower limit of zone 1 is located at approximately 10 mm below the nozzle tip; at this location, a symmetrical powder density profile, with a maximum at the center is obtained. A different behaviour is observed at higher power : a sharp decrease of transmission occurs in zone 2. This decrease is due to the higher absorption of the radiation by the heated powder, which begins to melt on the surface. At large distances from the nozzle (zone 3) about 40 % of the laser energy remains.

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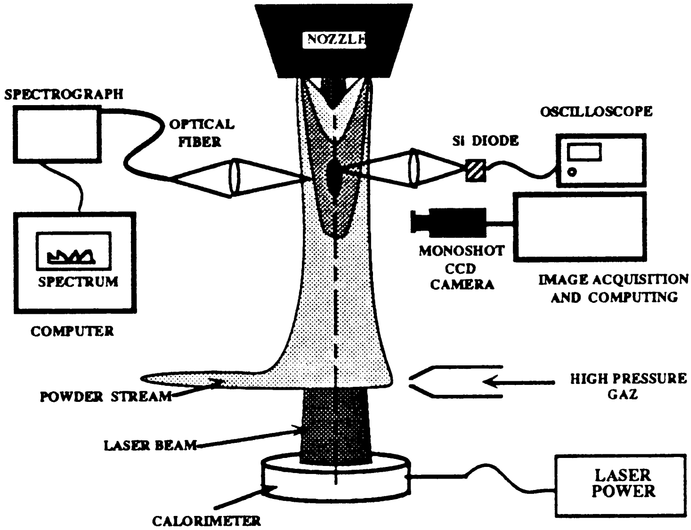

Fig. 6 : Experimental set-up used to study the interaction between the powder stream and the laser beam. Recorded signals are : laser radiation transmitted by the powder, temporal, spatial and spectral distribution of the photonic signals emitted by the heated powder.

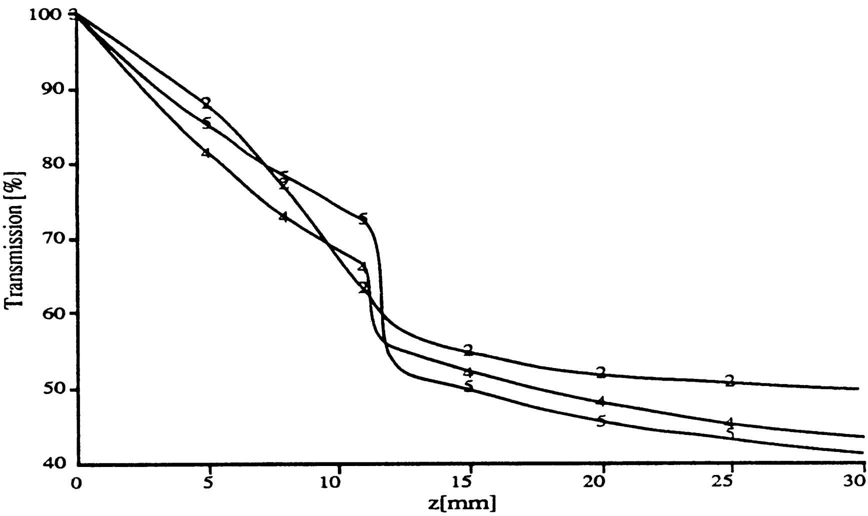

Fig. 7 : Transmission of the laser power by a stream of Stellite flown with Argon. Feeding rate : 30 g/mn. The 3 curves have been recorded for the following laser powers : 2 ->2 kW, 4 ->4 kW, 5 -> 5 kW.

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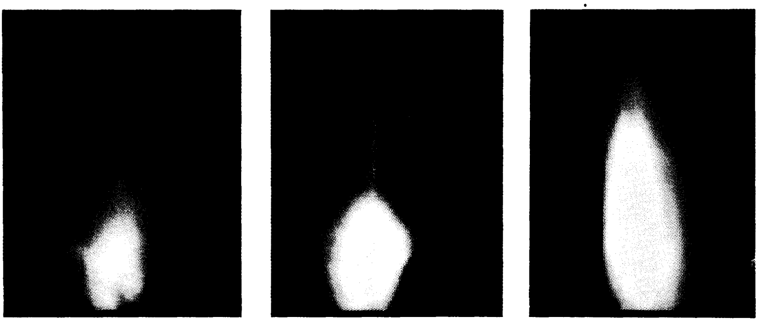
Spatial and temporal variation of the plasma

A monoshot CCD camera has been used to record the spatial distribution of plasma emission. Plasma is formed when excessive heating of a laser energy causes avalanche ionization in the irradiated medium. This phenomenon has been extensively studied in the process of welding [4], where a plasma is observed in the vicinity of the welded part. The plasma, where it arises, causes a drastic change in the propagation conditions of the laser beam. During cladding it is not possible to blow away the plasma since it appears in the incoming powder stream. It is then necessary to locate precisely the distance from the nozzle where plasma conditions exist. This limit depends on the laser power as it can be seen from Figure 8.



P = 3 kW P = 4.5 kW P = 5 kW

Fig. 8 : Spatial development of the laser-induced plasma in the powder. Stellite blown with Argon.

The exact location of gas-powder mixture breakdown cannot be precisely located. However, as it could be expected from transmission measurement, the mixture breakdown occurs closer to the nozzle as the laser power is increased. Spatial extension of the plasma cloud varies considerably. Photodiode measurement has established that at 5 kW, the plasma is permanent in the lower part of zone 2, and sporadic in the higher part. Plasma initiation takes place at a power close to 3 kW.

Spectroscopic observations

Emission by the powder has been recorded using a spectrograph. The signal has been collected from the center of the plasma plume. Figure 9 shows three partial spectra of the plasma observed in Stellite-Argon at the following laser powers : 4, 4.5 and 5 kW. At 4 kW, the spectrum is continuous. At higher power a line spectrum appears on top of the continuous one. We have observed in the complete recording, that the species responsible for the line spectrum are the powder components (Chromium in the case of

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Stellite) and not the Argon used to blow the powder. Similar results have been obtained with Helium instead of Argon.

From the experimental observations described above, it appears that, for a given powder material, there is a maximum distance from the nozzle where the sample can be placed.

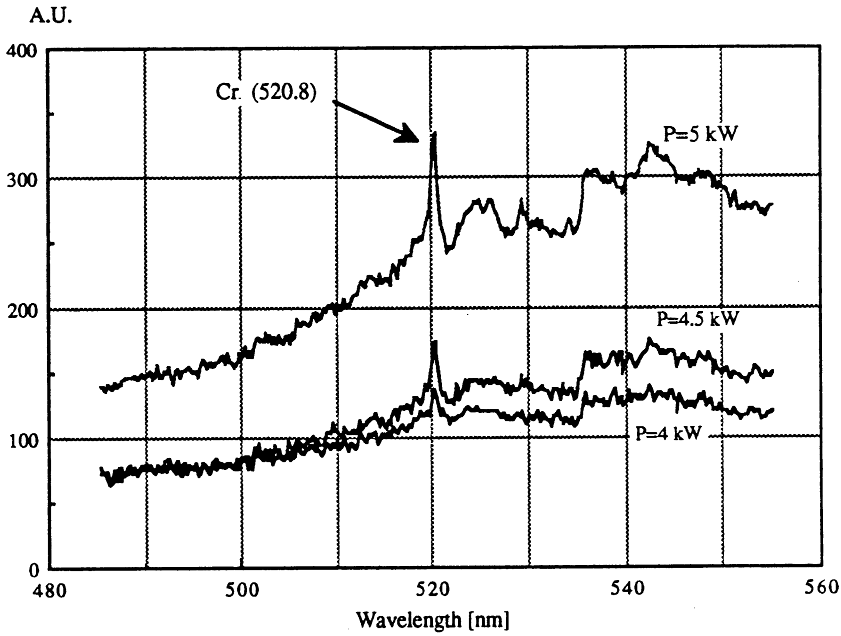

Fig. 9: Spectra of plasma induced in a stream of Stellite (Co 58%, Cr 30%, W 10 %, C 2%), recorded for three different laser powers. The spectra is recorded in the lower part of zone 2 defined on Fig. 5.

CONCLUSION

Laser cladding with coaxial powder feeding has been implemented. During the process, a significant part of the laser power is introduced directly into the powder, the remaining power being used to heat the substrate. The interaction between the powder stream and the laser beam has been investigated using calorimeter, a CCD camera, a Si photodiode and a spectrograph. These observations allowed us to identify the useful part of the interaction volume. Powder heating by the beam has appeared to be helpful for a maximum efficiency of the process. An efficiency as high as 80 % has been obtained. Plasma observed in Stellite at high laser power or for long interaction time between powder and laser beam, has been shown to be ignited by the metallic components of the mixture, with no influence of the carrying gas, if Argon or Helium are used. The position of the sample in the coaxial configuration is not too critical. These characteristics, combined with the independence of the process in relation with direction of motion, will make the described set-up useful for cladding curved surfaces.

ACKNOWLEDGMENT

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