THE SIMULATION OF THE ELECTRON BEAM SPOT CONTROL

Stelian Emilian Oltean, Mircea Dulău
Petru Maior University of Târgu Mureş
soltean@upm.ro, mdulau@upm.ro

ABSTRACT

Electron beams have many special properties which make them particularly well suited for use in materials processing, wherever conventional techniques failed or proved to be inefficient. The entire process has a lot of time varying parameters, so using a distributed control system for 3d position of the electron beam spot may improve the quality of the material processing. Matlab environment was used for model implementation and simulations of the control system which contains the focusing and deflecting components. Due the nature of the process and knowing the electron beam equipment we proposed for the simulations scenarios with a 3D virtual surface.

Keywords: electron beam material processing, modeling and simulation

1. Introduction

The electron beams properties like high resolution, long depth of field attainable, high power density energy make them very useful in many fields. One of these is material processing. So, electron beam can be used in melting, welding, evaporation, refining and thermal surface treatment material in microelectronics, nuclear technologies, aeronautics.

The electron beam equipment is a multivariable process which makes the modelling process a difficult task to solve. The heat absorption, the penetrations of the electrons in metal, focusing of beam are some of the complicated problems provided by the study of the equipment. Also, the examination of the electron gun's variable is very difficult due the nature of the process. These reasons are sufficient to look after modern control strategies. After these methods have been found, an important stage prior to their implementation is modelling and simulation.

The quality of the processing and the technical demands depend on the electron beam equipment variables such as electron beam current, accelerating voltage, focusing distance, electron beam speed, deflections in the Ox and Oy directions, electron beam diameter, focusing coil current and deflection coil current, electrons emission, vacuum in the work chamber or electron beam gun, electromagnetic fields, X radiation, material properties [1].

From the variety of parameters which can be chosen to be controlled, the focusing and the deflection of the electron beam have a lot of influence on the processing performance. So, we present in this paper some aspects from the modelling and simulation stage of the electron beam control system implemented in Matlab environment, considering a 3D virtual surface.

Because of the complex physical processes taking place in the electron beam focus point we designed in [2] a fuzzy adaptive focusing system which controls the energy density of the electron beam transmitted to the workpiece. The minimum spot diameter of the electron beam on the material surface provides the highest depth of penetration.

Deflecting system or/and mechanical movement with CNC table are used to cover all possible target points positions of the workpiece surface or to follow the seam trajectory. We designed in [3] a PI control system for linear deflection of the electron beam.

Combining these automatic systems (one focusing and two deflecting components for the Ox and Oy directions) result a multivariable 3d control of the electron beam spot. The reference signals for the focusing and deflecting systems are obtained using a 3d decomposition of the seam trajectory.

The paper is structured in three parts:

- the presentation of the electron beam equipment;
- the presentation of the 3d control system of the electron beam spot position;
- the presentation of the simulations for a case study using the electron beam 3d control.

In the final section of the paper some conclusions about the electron beam processing control are given.

The study of the documentation in this field and the experiments are currently being put into practice by the authors based on the electron beam equipment CTW 5/60 (5kW maximum power at 60kV accelerating voltage) developed by "Petru

Maior" University of Târgu Mureş in partnership with Electrical Research Institute ICPE Bucharest [4].

2. Electron Beam Equipment

The most common systems of this type used in manufacturing are high vacuum design. The main parts of the equipment are the triode gun and the vacuum system that provides high vacuum environment, without the beam cannot be generated.

The triode gun design consists of the cathode, composed of the filament and the massive cathode, electrode or grid, anode, focusing and deflection coils. The vacuum system ensures a pressure level of 10^{-3}–10^{-4} Pa and it is controlled by a multi-tasking digital system implemented on the microcontroller and PC. To avoid accidents, any error that may appear in this unit is pointed out and preparing sequences for material processing are halted [4].

The emission of electrons from the incandescently heated termoemission filament, which is saturated during the process by a predetermined amount of electrical current, generates the main beam. A negative high voltage potential is applied to the filament cathode assembly, referred to as the accelerating voltage of 40…60kV.

Another voltage, lower than the accelerating voltage is applied to the grid cup or bias assembly. In this way the grid cup acts as a valve that controls the volume of electron energy that can flow from the cathode to attracting targets.

The first target, situated in the triode gun, is an anode at a positive potential, which forms the beam. Then the focused beam of electrons is led using focusing coil to a secondary target, situated in the workbox, consisting of a metallic workpiece, where the kinetic energy of the electrons is converted into thermal energy and the metal is heated. The metallic workpice offers a conductive path to earth to complete the circuit. This target can be stationary and the electron beam energy deflected using deflection coils or the workpiece can be moved using a CNC table [1,4].

The high power electron beam system with the classic triode gun is shown in the Fig. 1. In this scheme the high voltage supply, high voltage controller, electron beam current controller and other intermediary or secondary modules are not drawn [4].

The magnetic focusing coil is located beneath the anode assembly and is circular in design and concentric with electron beam. An electrical current is passed through the coil, which produces magnetic fluxes that provides convergence of electron beam. The deflection coil is created with four wound coils positioned at right angles to the column.

Another important part in the experimental equipment is the electron's collector composed of the four electrodes used to capture reflected electrons from target surface (workpiece). These electrons offer utile information about the material processing.

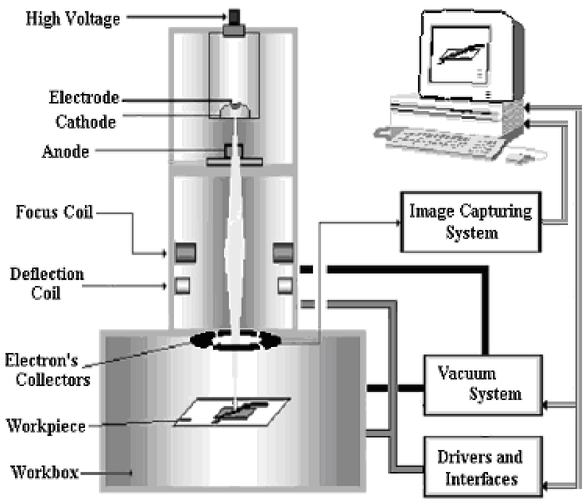

Fig. 1 – The electron beam equipment

3. Electron Beam 3D Control System

Usually following a regular trajectory on the workpiece surface with electron beam spot can be done with manual control of the deflecting and focusing systems or moving the CNC table. If the seam trajectory is complex in a random manner, the tracking process must be assisted by digital equipments and the desired seam is obtained using 3d control systems.

First of all, we proposed that seam trajectory is contained in 256x256 pixels digital images representing the 5x5cm^2 workpiece surfaces [5]. One of these images saved in grayscale bitmap format with 8bits per pixel is shown in Fig. 2.

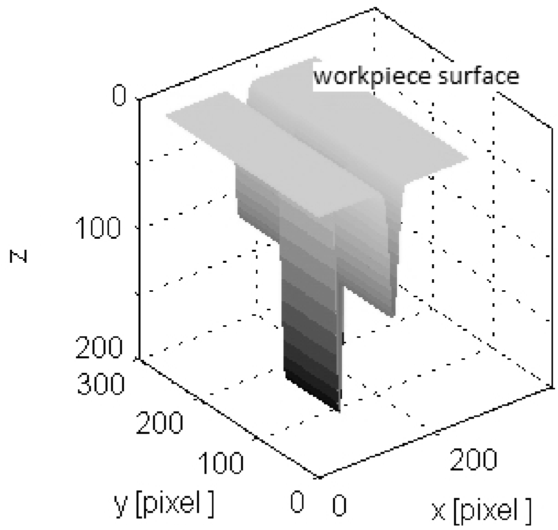

Fig. 2 – The 256x256 pixels digital image

The desired 3D seam trajectory that must be extracted from the 256x256 pixels digital image is presented in Fig. 3. Also, the three-dimensional axes was converted to the real physical values [3,5].

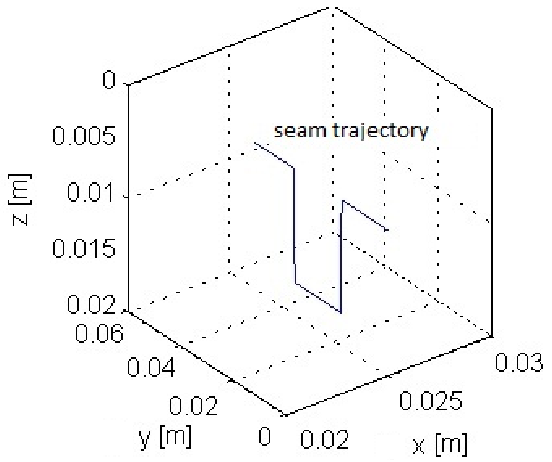

Fig. 3 – The 3d seam trajectory

Having the virtual trajectory, our next task was to design a 3d system which controls the movement of the electron beam spot in the material. The three dimensional control system scheme of the electron beam spot is shown in Fig. 4 [5].

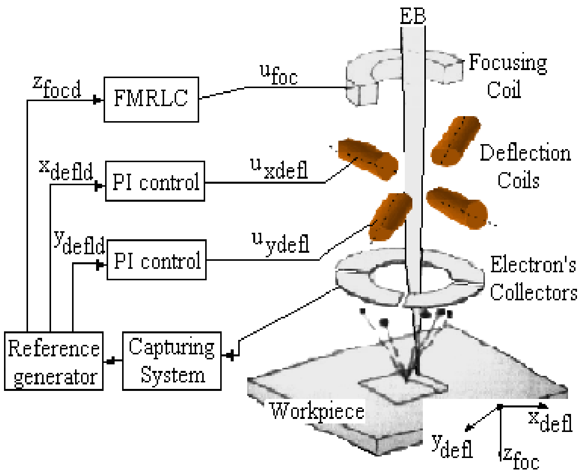

Fig. 4 – The electron beam 3d control system

The two deflecting coils, located beneath the focusing coil, create two magnetic fields; both are perpendicular to the symmetry axis of the electron gun. A constant deflection on the linear axis (Ox or Oy) needs a magnetic field with constant intensity generated by the one deflecting coil (Ox or Oy).

The magnetic fields created with both coils determine the position of the focal spot on the workpiece plane xOy. To prevent the aberrations of the magnetic lenses and deformations of the spot, the deflection is made on small angles. From this point of view the resulting maximum working area is $5cm^2$.

The mathematical model of the deflecting systems contains two components: the stationary model and the dynamic model.

The deflection of the electron beam on Ox axis x_{defl} depends on the deflecting current i_{xdefl} if the accelerating voltage U_{acc} is constant. The dynamic model of the deflecting system on the linear axis Ox is given by a first order differential equation [3,5].

$$x_{defl} \approx \sqrt{\frac{e_0}{2 \cdot m_e}} \cdot \frac{k_b \cdot \mu_0 \cdot d_{defl} \cdot l_b}{a \cdot \sqrt{U_{acc}}} \cdot n \cdot i_{xdefl}$$

$$L_s \frac{di_{xdefl}}{dt} + R_s i_{xdefl}(t) = u_{xdefl}(t) \qquad (1)$$

Where d_{defl} is the distance from the coils to the material surface, l_b the coil length, a the coil dispersion, k_b the induction curve, e_0 the electron charge, m_e the electron mass, μ_0 the absolute permittivity, n the number of turns , L_s the coil inductivity and R_s the resistance.

Due the nature of the deflecting system we designed in [3,5] a PI controller with 0.045 seconds integrative and 73.94 proportional constants. This controller was translated in discrete time form using Tustin method and 1 milliseconds sampling time.

In the Oy direction the process and controller models have similar forms.

Using the focusing coil the convergence of electron beam and Oz axis movement are assured at high precision. Mathematical model of the focusing system has also two components: the stationary model and the dynamic model [2,5].

The stationary model of the focusing system consists in the nonlinear dependencies between the number of turns n, focusing current i_{foc} and focusing distance z_{foc} [2,5]. The dynamic model has as input the prescribed focusing coil voltage u_{foc} and as output the focusing current i_{foc}.

$$z_{foc}(i_{foc}) \approx 85 \cdot \frac{m_e}{\pi \cdot e_0 \cdot \mu_0^2} \cdot \frac{R \cdot U_{acc}}{(n \cdot i_{foc})^2}$$

$$L_s \frac{di_{foc}}{dt} + R_s i_{foc}(t) = u_{foc}(t) \qquad (2)$$

Because the stationary model (2) is an approximation, influenced by the electron beam equipment variables, nonlinearity and disturbances we proposed in [2,5] a fuzzy model reference learning control FMRLC for the focusing system. This fuzzy adaptive system is capable to learn and to adapt to different unknown situations. FMRLC has the same structure as conventional model reference adaptive control MRAC, which is composed of four main parts: the plant, the controller, the reference model and the adjustment mechanism [6].

4. Simulations and conclusions

This section presents the results obtained using the multivariable control system of the electron beam spot which contains deflections on two axes and focusing in depth of the material.

The reference for every control loop of the distributed system is determined from the decomposition of the three dimensional seam trajectory on the Ox, Oy and Oz axes.

Along the Ox axis the reference is 2.5 cm step type. For Oy deflecting system the reference varies from 0 to 5 cm in 2.5 seconds (considering a 2cm/s movement speed). The reference for the third directing part (Oz axis) is a sum of the desired depth of the seam in the workpiece and the distance from the electromagnetic lens to the material surface.

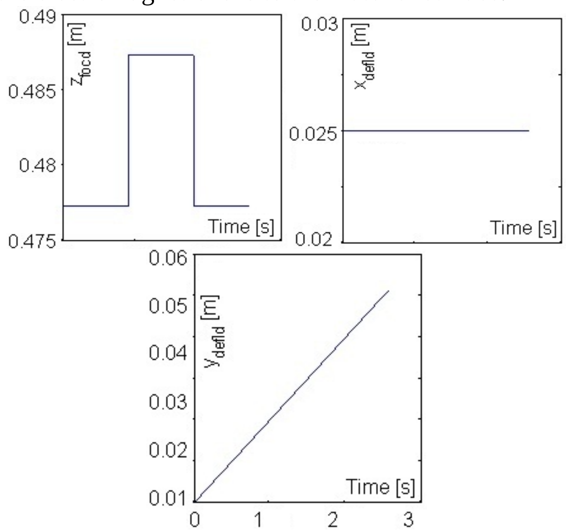

Fig. 5 – The decomposition of the seam trajectory

The responses of the 3d control system are shown in Fig. 6.

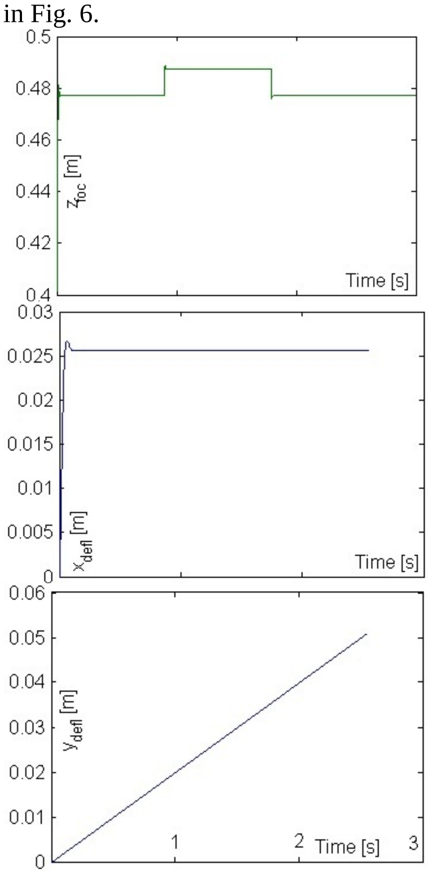

Fig. 6 – The responses of the 3d control system

It is obvious that the deflection on Ox axis x_{defl} tracks the reference signal x_{defld} obtained from the seam trajectory and steady state error is zero. The deflection on Oy axis y_{defl} follows the reference signal y_{defld} and steady state error resulting from the Fig. 5 and Fig. 6 converges to zero.

The focusing distance z_{foc} follows very closely the reference signal z_{focd} and for this component the steady state error converges also to zero. The demand for this module is carried out via the fuzzy adaptive control.

The response of the 3D control system represents the 3d position of the electron beam spot. The 3d response is shown in Fig. 7 and tracks the seam trajectory shown in Fig. 3.

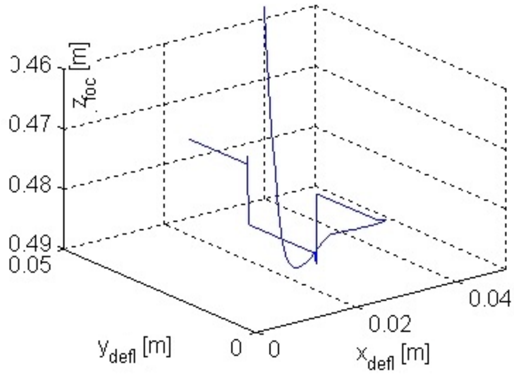

Fig. 7 – The 3D movement of the electron beam

In conclusion, the electron beam processing system is complex with many variables, which make it very hard to be controlled. Focusing distance control and trajectory tracking are the final stages of automation in the electron beam equipment. So, these can be used to improve the quality of the processing.

The major problem is provided by the focusing component, because the overfocused or underfocused beams are some effects that must be avoided. The paper presented o distributed 3d control which combines the deflections components with the focusing part. The results of simulations shown in this paper indicate the possibility to perform a distributed and modern strategy control of the 3d spot position of the electron beam.

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