ADVANCED CONTROL OF THE ELECTRON BEAM WELDING

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Abstract: *The material processing with the electron beams solves great topical problems, wherever conventional techniques proved to be inefficient. Material processing involves many complex phenomenons like the electrons generation, beam forming and transport, heat absorption in the workpiece. The information about the heated surface with electron beam is obtained only using the electrons reflected from the material surface. So, modern control strategies using artificial intelligence, adaptive and expert systems implemented on digital systems are required to produce high quality material processing. In this paper we present advanced methods used to control the energy density of the electron beam transmitted to the workpiece. The multivariable control system has three directing components: the focusing system dedicated to focus distance control and two deflecting systems for the joint tracking. The desired references for these components are determined from the digital images constructed using the electrons reflected from the material surface.*

Keywords: *Electron Beam Welding, Image processing, Fuzzy Model Reference Learning Control*

1. INTRODUCTION

Electron beam material processing is an important non-conventional technique for the industrial manufacturing. Nuclear technologies, aeronautics, microelectronics are some examples where this equipment is used. Industrial applications of electron beam techniques begin around 1950. The special electron beams properties like high resolution, long depth of field attainable, high power energy density make them very useful in material handling.

An electron beam system can be used in melting, welding, evaporation, refining and thermal surface treatment process. In fact, electron beam and laser are the only ways of delivering large amounts of concentrated thermal energy to materials (maximum 10^8 W/cm^2) [1].

The heat absorption, the penetrations of the electrons in metal, focusing of beam are rather complicated, making their modelling a difficult task to solve. Also, the examination of the electron gun's variable is very difficult due to the nature of the process. The heating process depends on the electrons emission, electromagnetic fields, X radiation, material proprieties. Thus it is a necessity of a modern control strategies implemented on digital systems to produce material processing at high quality and required standards.

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 I.C.P.E. Bucharest [2].

The paper is structured in four parts as follows:

- the presentation of the electron beam processing principle, system's variables and welding parameters;
- the presentation of some image processing methods used to detect the seam trajectory and decomposition of this in three references;
- the presentation of the electron beam three dimensional control using focusing and deflecting systems;
- the presentation of the experimental results for a case study using the electron beam 3d control.

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

2. ELECTRON BEAM PROCESSING SYSTEM

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

The high power electron beam system with the classic triode gun is shown in the figure 1. In this scheme the high voltage supply, high voltage controller, electron beam current controller and other secondary modules are not drawn [3].

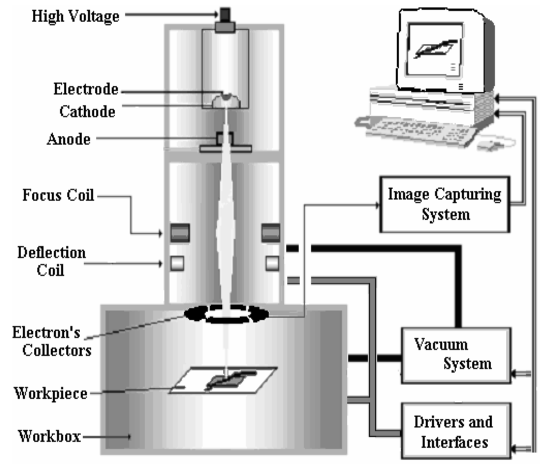

Fig. 1. Electron Beam Processing System

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 multitasking digital system implemented on the microcontroller and on PC. To avoid accidents, any error that may appear in this unit is pointed out and preparing sequences for material processing are halted.

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. 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 [2,4].

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 electron's collectors composed of the four electrodes used to capture reflected electrons from target surface (workpiece). These electrons offer utile information about the material processing

2.1 Electron Beam Processing Parameters

Some of the parameters of the electron beam equipment which characterize the processing are the electron beam current (I_f), accelerating voltage (U_{acc}), focusing distance (z_{foc}), deflection in the Ox and Oy directions (x_{defl}, y_{defl}), electron beam speed (v), electron beam diameter (d_f), focus and deflection coil currents (i_{foc},i_{defl}) [5].

The depth (h) and width (b) of welding penetration, the specific power of the electron beam (P_{sf}) and the heat affected zone HAZ of the material depend on the beam diameter on the surface of the material, which is a function of focusing distance. We consider constants the electron beam current, accelerating voltage and electron beam speed [5].

Figure 2 shows the weld parameters h and b.

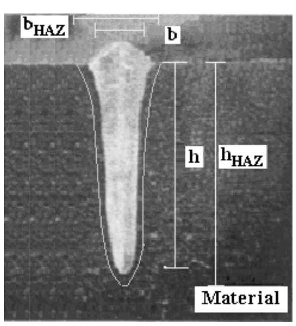

Fig. 2. The Weld and the HAZ

Relation between specific power, depth, width and the beam diameter are:

$$P_{sf} \cong \frac{I_f \cdot U_{acc}}{\pi \cdot d_f^2 / 4} \tag{1}$$

$$h = \frac{2 \cdot U_{acc} \cdot I_f}{v \cdot d_f \cdot H \cdot \left[1 + 1.2 \cdot \lambda \cdot \left(\frac{1}{d_f \cdot v} + \frac{1}{2 \cdot a_t}\right)\right]} \tag{2}$$

$$b = 2 \cdot \sqrt{\frac{I_f \cdot U_{acc} \cdot \eta_i \cdot \eta_t \cdot d_f}{\pi \cdot v \cdot h \cdot H}} \tag{3}$$

Where a_t is thermal diffusion coefficient, λ thermal conductivity, η_i - electrical effiency, η_t thermal effiency, $H=c \cdot \rho \cdot (Tt-273)+Ht$, c heat absorption capacity, ρ density, T_t melting temperature and H_t melting latent heat.

In the final stage of the electron beam equipment the tracking trajectory (stochastic case) on the surface of a stationary workpiece is obtained using the deflecting systems and the desired depth of penetration (depth/width ratio) is achieved with the aid of the focusing system.

Combining these automatic systems results a multivariable 3D control of the spot of the electron beam. The reference signals for the deflecting and focusing systems are obtained with a decomposition of the seam trajectory detected via image capturing system [6].

3. SEAM TRAJECTORY DETECTION

Usually welding after a regular trajectory with electron beam can be done with manual control of the deflecting systems or moving the CNC table.

If the seam trajectory is more complex in a random manner the welding process must be assisted by digital equipments. The desired seam trajectory is determined in this case using the images of the material surface and some image processing methods. Then, this 3D seam trajectory is decomposed on the Ox, Oy, Oz axes. So, we compute the references for the directing systems in three steps:

- digital image reconstruction of the material surface using the capturing system;
- 3D seam detection using image processing methods;
- decomposition of the 3D seam trajectory in the three references for the focusing distance system (z_{focd}), Ox deflecting system (x_{defld}) and Oy deflecting system (y_{defld}).

The block diagram of the image capturing system is shown in figure 3. This part is very important to control the electron beam focal spot, because offers the qualitative and quantitative information about the process [2,3,4].

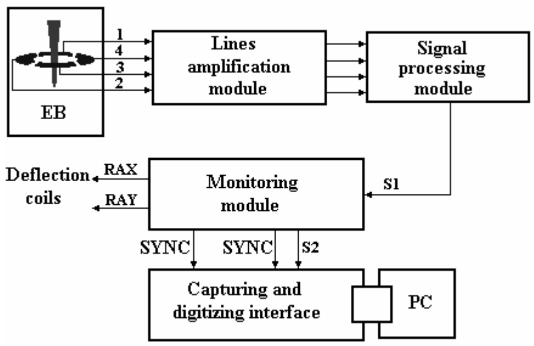

Fig. 3. Image Capturing System

The four electron's collectors give electrical signals proportional to the reflected electrons from the material surface. These signals are amplified, filtered and processed in the capturing system to obtain the surface image.

The lines amplification module contains four amplifiers for amplification of the signals provided by the four electrodes. After amplification the signal processing module assures the reduction of the additive noise. This module also combines the four signals for elimination of the distortions generated by the asymmetric capture of the reflected electrons and provides an analog signal S1 proportional to the reflected electrons. Different configurations for combining the four signals from the collectors are possible (1+3, 2+4, 1+2+3+4).

The monitoring module contains the generators for EB deflection in a raster form (with RAX and RAY) and complex video formation block. From the RAX saw tooth signal for the horizontal deflection is formed the digital horizontal synchronization signal (SYNCO). The horizontal frequency used is 15.338 kHz. Dividing the digital horizontal synchronization signal with 256 we achieve the digital vertical synchronization signal (SYNCV).

Via capturing and digitizing interface images of 256x256 pixels representing the $5x5cm^2$ workpiece surfaces are recorded using special software on a personal computer. These images are saved in grayscale bitmap format with 8 bits per pixel.

Figure 4 shows an example of surface material image obtained via image capturing system.

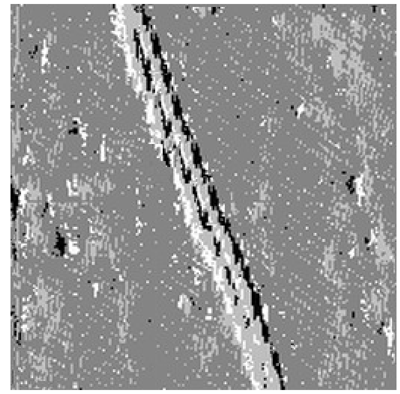

Fig. 4. The Image of the Material Surface

The primary images saved on hard drive contain the 3D seam trajectory. To detect the desired trajectory we use some image processing methods implemented in Matlab Toolbox [7]:
- median filtering;
- binarization;
- compute the complement of binary image;
- binary flood fill;
- skeletonization.

The first image processing method applied to the primary image is a median filtering (Figure 5). The method determines the value of an output pixel as median of the neighbourhood input pixels (the size of neighbourhood is 3x3). We use the median filtering to remove the outliers without reducing the sharpness of the image.

Detection of the seam trajectory is simplified if we compute binary images. A binary image has just two gray levels (black and white) corresponding to the object and the background. Binarizations (Figure 5) emphasize the structural characteristics of the images and distinguish the objects from the background.

Conversion of the 8 bits per pixel grayscale image in binary image is based on threshold. The global threshold of the filtered image is calculated using Otsu's method, implemented in Matlab Toolbox with graytresh function [7]. This method chooses the threshold to minimize the intraclass variance of the thresholded black and white pixels.

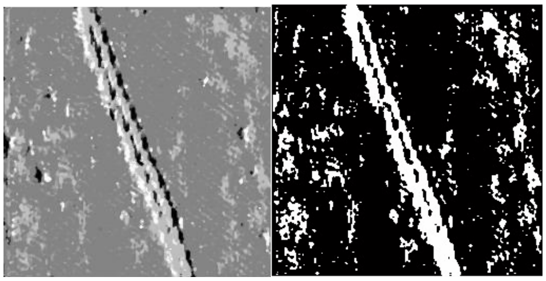

Fig. 5. Filtered and Binary Images

Because in binary images white represents the background we need to invert the image from figure 5 to accentuate the seam trajectory. The binary images from figure 5 and 6 contain in addition to the seam trajectory some unwanted pixels. Flood fill operation eliminates this noise introduced by the image capturing system.

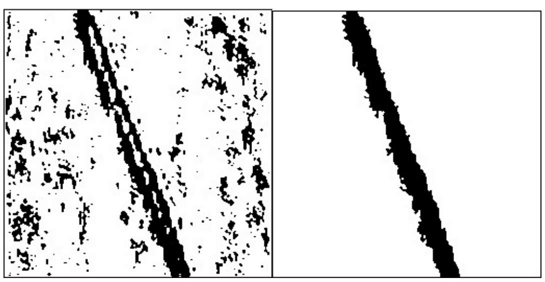

Fig. 6. Modified Binary Images

The seam trajectory is obtained from the cleaned image using morphological operations. We reduced black object in the surface image to a line, representing the seam trajectory.

The figure 7 shows the skeletonization process and a superposition of the 2D seam trajectory and primary image initially captured.

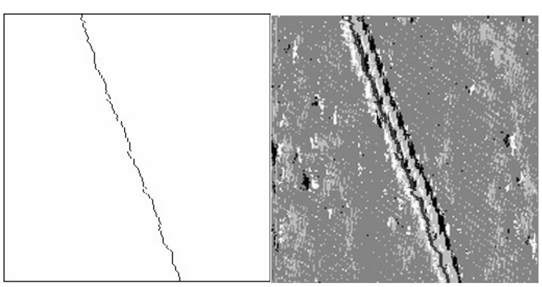

Fig. 7. 2D Seam Trajectory and Primary Image Captured

The seam trajectory from the binary image decomposed on the Ox and Oy directions gives the reference signals for the deflecting systems, x_{defld}, y_{defld}.

The reference signal for the focusing system is obtained using the primary image of the surface. The 8 bit values of the pixels on the 2D seam trajectory correspond to the depth in the workpiece. Recording these values we will have the time dependent depth shape, which actually is the reference on the Oz direction.

The reference signals for the deflecting and focusing systems are shown in figure 8.

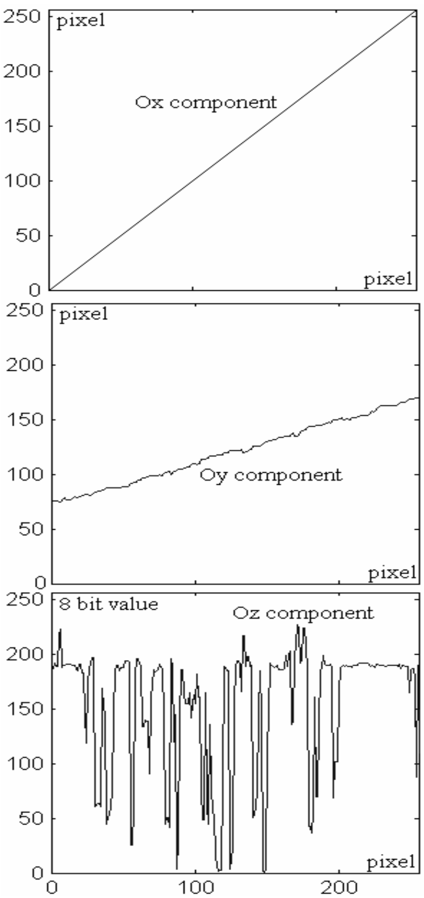

Fig. 8. Decomposition of the 3d Seam Trajectory for the Deflecting and Focusing Systems

The signals from figures 8 must be scaled and converted to the practical values (time and length). For example if 256x256 pixels image represent the $5x5cm^2$ surface of the material (1pixel≈0.0195cm) and considering a 2cm/s welding speed the 256 pixels are covered in 2.5 seconds.

4. ELECTRON BEAM CONTROL SYSTEM

Electron beam control system contains two types of control: classical PI for the deflecting components and fuzzy adaptive (Fuzzy Model Reference Learning Control FMRLC) for the focusing component [6].

The deflecting system has a mathematical model with a stationary part and a dynamic part [3,6]. Stationary model is a particular solution of the dynamic equations of the electrons when the electric and magnetic field distribution is known. The relation between the deflection distance on the linear axis Ox and the deflection coil current is:

$$x_{defl} \approx \sqrt{\frac{e_0}{2 \cdot m_e}} \cdot \frac{k_b \cdot \mu_0 \cdot d_{defl} \cdot l_b}{a \cdot \sqrt{U_{acc}}} \cdot n \cdot i_{xdefl} \tag{4}$$

Where d_{defl} is the distance from the coil to the material surface, l_b the coil length and a the coil dispersion constant.

The dynamic model of the deflecting system on the linear axis Ox is given by the relation 5.

$$L_s \frac{di_{xdefl}}{dt} + R_s i_{xdefl}(t) = u_{xdefl}(t) \tag{5}$$

The inductivity L_s and resistance R_s characterize the dynamics of the deflecting coil.

Due the nature of the deflecting system we designed in [6] a PI controller which gives the desired performances (*σ=4.3%, εst=0*). The PI controller has 0.045 seconds integrative and 73.94 proportional constants. This controller was translated into discrete time form using Tustin method and 1ms sampling time.

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

The focusing system is one of the most important control systems of the electron beam equipment automation because allows to attain the desired depth of electron beam penetration. Mathematical model of the focusing has two components, too.

Including the magnetic field distribution and using some optics concepts from the dynamic equations of the electrons that cross through the electromagnetic coil results the stationary model of the focusing system. This approximate model consists in the nonlinear dependencies between the number of turns, focusing current and focusing distance [3,6].

$$z_{foc}(i_{foc}) \approx 85 \cdot \frac{m_e}{\pi \cdot e_0 \cdot \mu_0^2} \cdot \frac{R \cdot U_{acc}}{(n \cdot i_{foc})^2} \tag{6}$$

The relation 7 gives dynamic model of the focusing electromagnetic lens.

$$L_s \frac{di_{foc}}{dt} + R_s i_{foc}(t) = u_{foc}(t) \tag{7}$$

This dynamic model has as input the prescribed focusing coil voltage u_{foc} and as output the focusing current i_{foc}. The inductivity L_s and resistance R_s characterize the dynamics of the focusing coil.

Because the relation 6 is an approximation of the electron beam focusing model, influenced by the electron beam equipment variables, nonlinearity and disturbances we implemented a fuzzy model reference learning control FMRLC [3,8].

FMRLC (Figure 9) 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. Comparatively to MRAC systems the FMRLC make only local changes to the controller's rule base. This local learning plays an important part since it will allow the controller to remember the adjustments made in the past, when it will encounter similar working conditions [9,10].

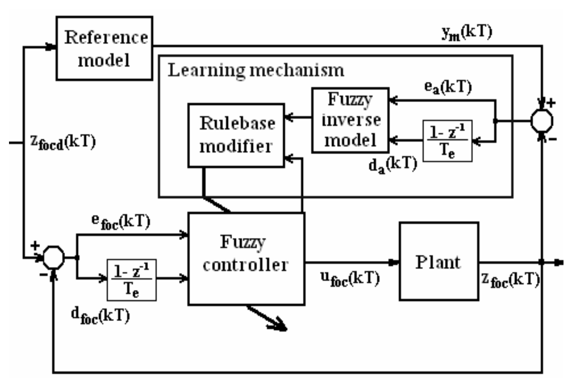

Fig. 9. FMRLC for the Electron Beam Focusing

The learning (adaptation) mechanism uses the adaptation error e_a to adjust the fuzzy controller's parameters to obtain the desired trajectory for the focusing distance z_{foc}. The focusing distance will generate the desired depth of penetration of the electron beam.

The reference model, which characterizes the desired performance of the system, can take any form (linear or nonlinear equations, transfer functions, numerical values etc.). In this case the reference model is 1, because we want to follow the shape of seam depth (included in z_{focd}).

The schematic diagram of the electron beam 3d control which contains the deflecting and focusing stages is shown in figure 10 [3, 8].

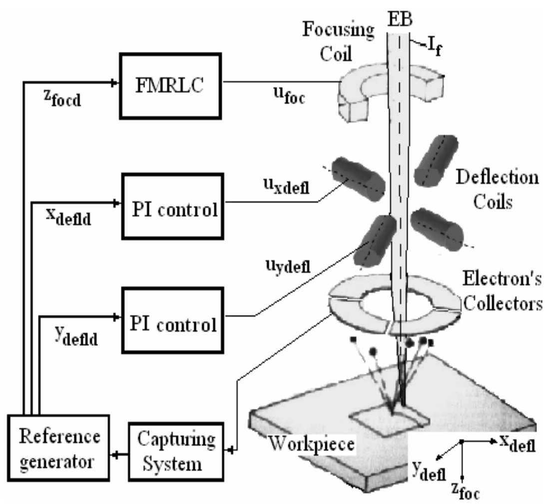

Fig. 10. Electron Beam 3d Control System

5. RESULTS

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

However, to avoid any risk, the seam trajectory detection, electron beam control and welding process must be supervised by the operator.

All control schemes were tested using the references signals determined on Section 3 and scaled to practical values. The aim for this control problem is to follow the 3d seam trajectory detected from the material surface image.

For Ox deflecting system the reference from figure 8 varies from 0 to 5cm in 2.5 seconds. The reference signal, the response of the system (Ox component of the welding trajectory) using PI controller, the command voltage applied to the coil and control error are shown in figure 11.

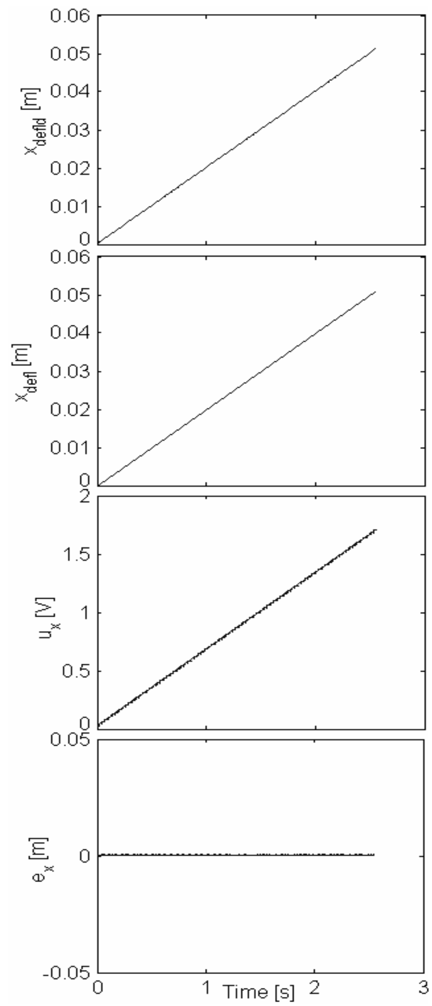

Fig. 11. Reference, Deflection, Command and Control Error on Ox

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 shown in figure 11 is zero.

For Oy deflecting system the reference signal, the response of the system (Oy component of the welding trajectory) using PI controller, the command voltage applied to the coil and the control error are shown in figure 12.

The deflection on Oy axis y_{defl} follows the reference signal y_{defld} for this component and steady state error shown in figure 12 converges to zero.

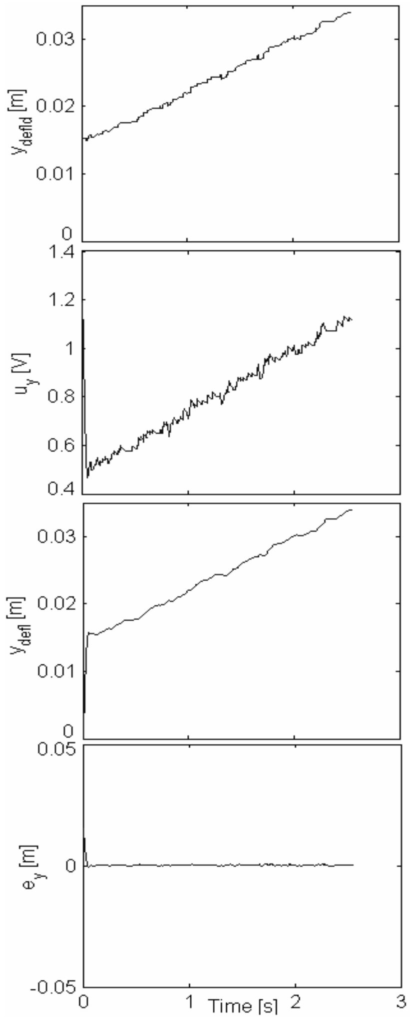

Fig. 12. Reference, Deflection, Command and Control Error on Oy

The component for Oz axis *z(kT)* of the 3d trajectory representing the shape of the seam depth is first filtered to eliminate the noise and oscillations. For the filtering operation we use a digital filter having the continuous equivalent of the first order lag element. This component *z(kT)* is than added to the distance value from the focusing coil to the workpiece (*zf≈0.45m*) [8].

The reference signal for the focusing system (Oz component) is calculated with relation 8 and shown in figure 13.

$$z_{focd}(kT) = z_f + z(kT) \tag{8}$$

Figure 13 shows the evolution of the Oz focusing system reference and the response signal, the command voltage applied to the focusing coil, the control error and the adaptation (learning) error.

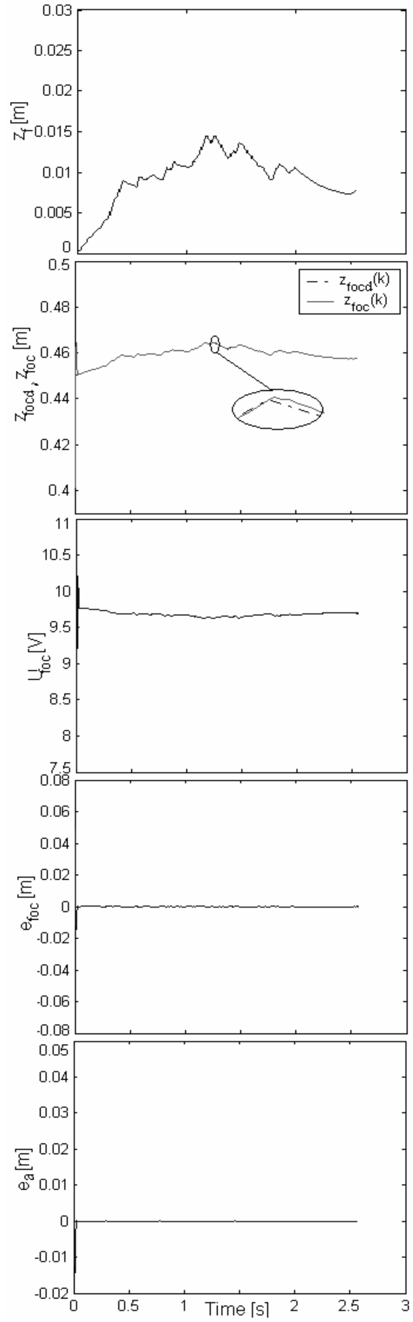

Fig. 13. Seam Depth and Functional Signals on Oz

The focusing distance z_{foc} follow very closely the reference signal z_{focd} for this component and steady state error shown in figure 13 converges to zero. This demand it is carried out via the fuzzy adaptive control. The learning mechanism uses the learning error e_a to modify the fuzzy controller parameters.

It is known that the performances of the adaptive and intelligent systems are superior to those of the classic control schemes, especially in case of time varying parameters of the process or in the presence of disturbances and nonlinearities.

6. CONCLUSIONS

This paper presented some advanced methods used for electron beam 3d control.

The electron beam processing system is complex with many parameters, which make it very hard to be controlled, but which offers great possibilities and high quality operations. The high depth and reduced width of welding penetration, the specific power of the electron beam in focal point and the small heat affected zone (HAZ) of the material are some characteristics that depend on the digital control.

Focusing distance control and trajectory tracking are the final stages of automation in electron beam equipment. The plant modelling, parameters determinations, the disturbance influences and variable information about the material processing are difficult tasks to solve. So, modern and distributed strategies are recommended in these situations.

The information about the process is obtained via image capturing system in a hidden form. These images must be processed first using image processing methods. Such methods and the images were presented in the section 3. Because the 3d electron beam control uses three directing modules (two deflecting systems and one focusing system) the 3d seam trajectory is decomposed in three components on Ox, Oy and Oz axes.

Due the nature of the process the deflection on Ox and Oy axes is obtained with PI control and the focusing is achieved with a fuzzy adaptive control (FMRLC type). The electron beam focusing is hard to be modelled and it is influenced by nonlinearities, disturbances and other equipment parameters. The big advantage of the fuzzy model reference learning control is given by the learning mechanism which assures that focus distance follows the desired trajectory and in this way high performances and the quality of material processing are carried out.

The results of the PI and fuzzy adaptive control shown in section 5 show the possibilities to perform a distributed and modern strategy control of the focal spot 3d position of the electron beam in the workpiece material.

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