

Automation of the electron-beam welding process

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Abstract. In this work, the automatic control is considered of the vacuum and cooling systems of the located in the IE-BAS equipment for electron-beam welding, evaporation and surface modification. A project was elaborated for the control and management based on the development of an engineering support system using existing and additional technical means of automation. Optimization of the indicators, which are critical for the duration of reaching the working regime and stopping the operation of the installation, can be made using experimentally obtained transient characteristics. The automation of the available equipment aimed at improving its efficiency and the repeatability of the obtained results, as well as at stabilizing the process parameters, should be integrated in an Engineering Support System which, besides the operator supervision, consists of several subsystems for equipment control, data acquisition, information analysis, system management and decision-making support.

1. Introduction

Over the years, the electron beam became a flexible and cost-effective manufacturing tool. Due to the deep penetration in the work-piece, the electron beam is able to generate deep and narrow welds with a minimal thermally affected zone without the use of welding consumables. The high vacuum required by the method prevents the heated and melted material from oxidizing and being affected by atmospheric contamination. With the development of advanced computer control, the number of electron-beam applications has increased significantly. In what concerns new applications of the electron-beam welding (EBW) technologies [1], the EBW plants turned into complex equipment containing highly stabilized power sources and electronic units, reliable and effective vacuum systems, technological chambers with precision 3D manipulators, thus becoming truly software controlled and programmed manufacturing tools with high efficiency and excellent reproducibility. The technological data gathered during the process enable one to monitor the quality and support the improvement of the testing process of the manufactured components; these data can be recorded for future analysis of the relations between the adjusted process parameters and the quality and stability of the welds.

In this paper, some aspects of the development of an Engineering Support System (ESS) are considered. The first step of this process is the choice of the ESS architecture and specification of the functionality of the implemented interactive sub-systems. The automation of the equipment control

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sub-system is considered in more detail in view of a practical realization that will help the implementation of a fully integrated ESS.

2. Engineering support system (ESS)

A fully integrated ESS can be defined as an information system that supports the analysis, design, implementation and operation of the technological process and its elements, based on knowledge, defined principles and recommended practices. The main aim of developing an ESS for EBW is to integrate and organize the knowledge on the process and to use this knowledge to improve the modeling and control capabilities, their efficiency, adaptability, flexibility and re-configurability, as well as to achieve integration with other technological processes that can be performed on the same equipment, as surface modification, evaporation and thin-layer deposition, selective electron-beam melting, etc.

Usually, the electron-beam installations operate in a semi-automatic control mode. Even in the cases of highly-sophisticated computer controlled processes, the automation (including vacuum pump system, vacuum pressure control, cooling system control, manipulator control, processor-based high-voltage and emission-current control, electron-beam motion control and its characterization, PC-based automatic beam-power distribution, data acquisition and archiving etc.), operator supervision of the process and manual tuning are still required. The best practice shows [2-4] that modeling and simulation, when combined with a Decision Support System (DSS), can provide an organization of the tools necessary to make good business-case decisions by integrating the models, the data that drive the simulations and the optimization tools. A way to integrate the DSSs (combined with Data Collection and Acquisition, Information Analysis and System Management agents) with the automation (and/or manual) control and observation during the performance of EBW is the development of an ESS.

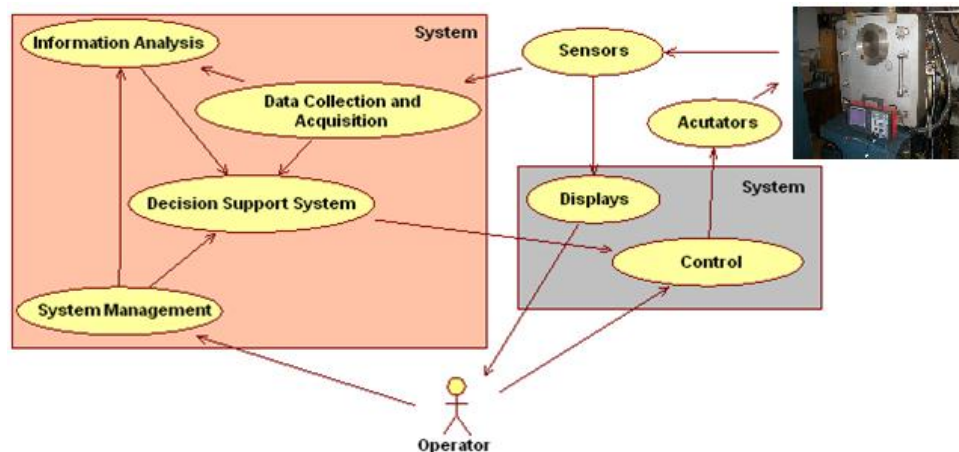


Figure 1. Engineering Support System architecture as a 'use-case' diagram.

The particular ESS architecture chosen [4] is presented as a UML use-case diagram in figure 1. The basic use-cases of the EBW ESS are: Data Collection and Acquisition (DCA), Information Analysis (IA), Decision Support System (DSS) and System Management (SM). They should be integrated with the System for **Equipment Control (EC)** in order to realize a working ESS.

The IA sub-system integrates:

- analytical modeling of the different processes – providing the DSS or the user with the control algorithm with calculated data (weld geometry parameters, weld defects, temperature distribution, etc.),
- statistical modeling and quality management and data analysis,
- information modeling,

- data-base management – different materials, models, experimental data, regime conditions, etc.,
- process parameters optimization.

The Decision Support System implements the results from the DCA, IA and SM sub-systems in order to provide the decision makers, the operators and managers with key information that enables them to make more efficient and consistent decisions. The System Management sub-system involves the definition of requirements and parametric constraints.

The System for **Equipment Control (EC)** (automated and/or manual) is usually designed by the EBW equipment manufacturers. It includes sources of actual measurement of data for the state of the EBW equipment by sensors or other measuring devices – **Monitoring agents (MoA)**, such as: vacuum pump system, vacuum pressure control, processor-based high-voltage and emission-current control, PC-based automatic beam-power distribution control, data acquisition and archiving etc. The **Control Agents (CA)** – actuators – execute the control algorithms. During the real-time control, the CA interfere with the EC block by some industrial controller device or following operator manipulation with CA. It is possible to apply different control algorithms (PID, fuzzy, adaptive etc.) after receiving the signals from the measuring devices thus implementing state feedback regulators. The MoAs follow the system behavior after applying the recommended method for designing and control. In the case of standard EBW control systems, the described two agents, together with the Data Collection and Acquisition sub-system are available. If all requirements are satisfied, then MoAs update the database by newly achieved results (solutions) for next re-use and application. Otherwise MoA and CA have to repeat their operations. The loop is performed at regular time intervals.

In order to automate the EC system of the EBW equipment considered, development of EBW control algorithms are needed, involving existing and additional technical means for automation, identification of transitional processes, control of static processes, development of control models and Programmable Logical Controller (PLC) based algorithms.

3. EBW control algorithm

From a system engineering point of view, the EBW is a complex system of processes that can be engineered to accomplish specific business and technological objectivities. The main features of an EBW plant, which must be taken into consideration by the ESS development, are the following: vacuum level (5×10^{-4} hPa), power density (2 kW/cm^2) available for welding of different materials, local superheating, precise control of the beam and welded samples motion, as well as automation of the process.

The EBW vacuum and cooling systems control algorithm, as a sequence of operations of starting and shutting down the EBW equipment, timing and performance criteria, as well as the actions in two major emergency situations – a water supply interruption and electricity cuts are presented in figure 2. The timing and performance criteria for each separate operation, if they are available, are presented above the corresponding block.

When starting the EBW installation, it is necessary to take into account the ambient temperature, which is a condition for the initial heating of the rotary pump (RP1) oil. If the temperature is above 20°C , we move to the next operation and start the RP1 on a gas ballast mode. The check for availability of electricity and water must be carried out continuously by appropriate technical means.

In order to improve the operation of the EBW installation in emergency situations, we recommend building of sound and light alarms, air-cooling for the diffusion pump and the use of alternative supply (UPS).

4. Experimental conditions

Following the control algorithm, experimental starting and stopping of the installation for electron-beam welding were performed. There are two processes, which limit the shortening of the starting and shutting-down time – reaching the necessary level of the vacuum in the chamber at the start and

cooling the diffusion pump when stopping the EBW equipment. This is why they are investigated here in order to make further improvements.

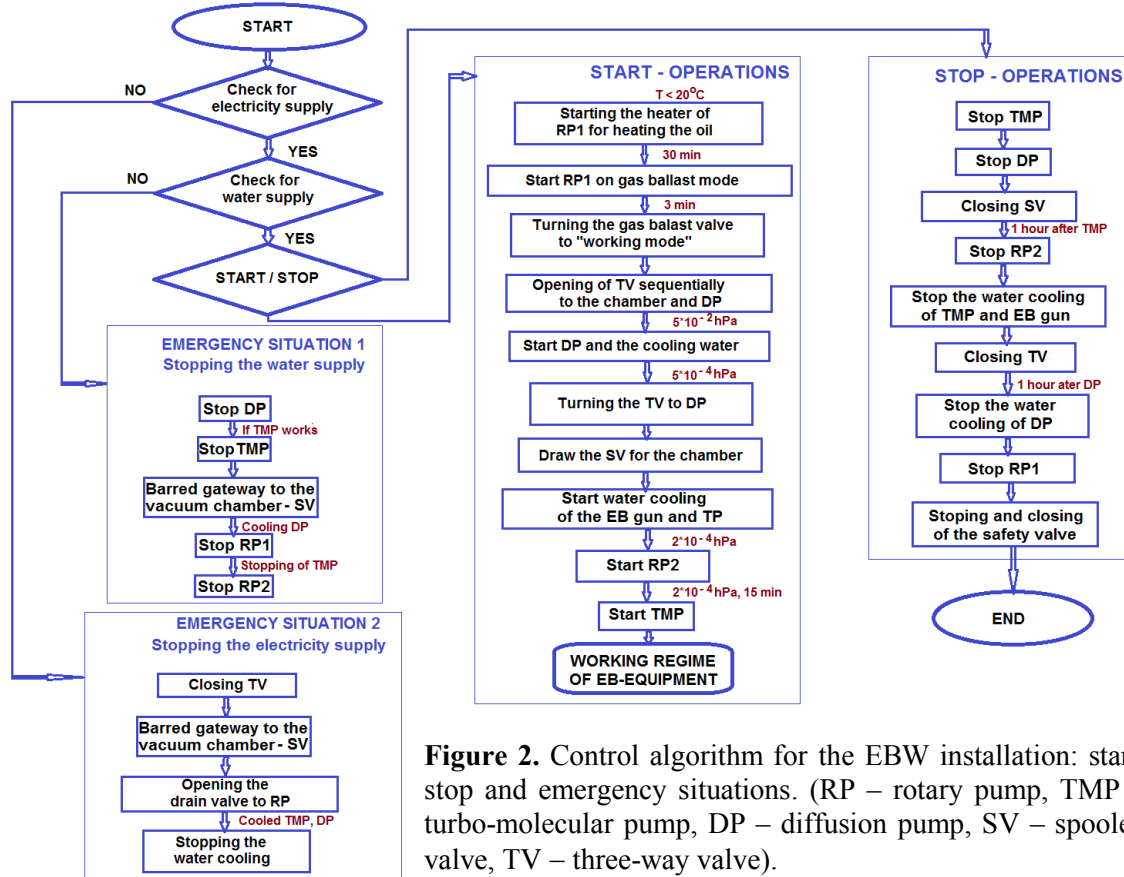


Figure 2. Control algorithm for the EBW installation: start, stop and emergency situations. (RP – rotary pump, TMP – turbo-molecular pump, DP – diffusion pump, SV – spooled valve, TV – three-way valve).

The temperature of the diffusion pump and the readings from the sensors for high and low vacuum level were considered. The total duration of the experiment was 5 hours and 15 minutes. This time did not include the realization of the technological process of electron-beam welding of materials, evaporation or surface modification, but merely the time needed for the equipment to reach the corresponding operating mode followed by the shutting down procedure. The optimization and management of this time interval is associated with both optimal management of the technical means available and the introduction of new ones with more flexible management and with better parameters or support functions. Figure 3 is a graph of the input pulses which represent the starting or stopping of the pumps - diffusion pump (DP), turbo-molecular pump (TMP) and two rotary pumps (RP1 and RP2).

The results of the measurements of the temperature of the diffusion pump (DP, in °C), the pressure in the zone of the sensor for low pressure (LP, in hPa) and the pressure in the zone of the sensor for high pressure (HP, in hPa), depending on the working time, are presented at figures 4, 5 and 6, correspondingly.

5. Identification of the transitional processes

The transitional functions of the temperature of the diffusion pump (DP), the pressure in the zone of the sensor for low pressure (LP) and the pressure in the zone of the sensor for high pressure (HP) are estimated on the basis of the experimental data obtained. The gains k ($k = \Delta y = y(0) - y(\infty)$) and step input signal $u(t) = 1(t)$, the time constants T and time delays τ (defined from the beginning of the experiment) are defined.

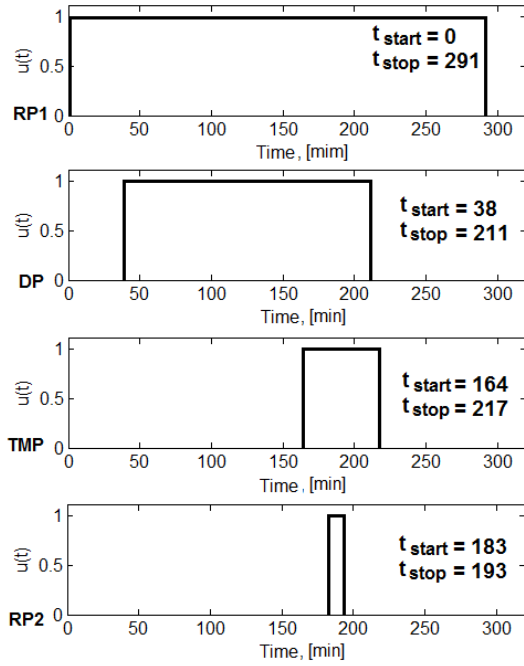


Figure 3. Input signals representing the starting or stopping of the pumps – diffusion pump (DP), turbo-molecular pump (TMP) and two rotary pumps (RP1 and RP2).

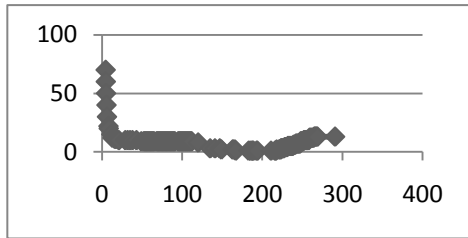


Figure 4. Temperature of the diffusion pump (DP), °C, depending on the working time.

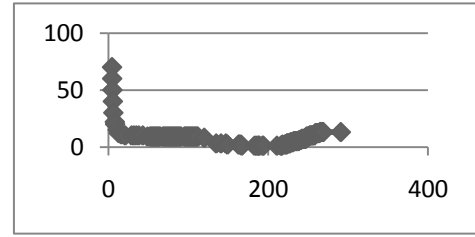


Figure 5. The pressure in the zone of the sensor for low pressure (LP) in hPa, depending on the working time.

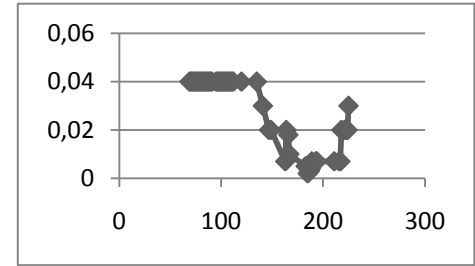


Figure 6. The pressure in the zone of the sensor for high pressure (HP) in hPa, depending on the working time.

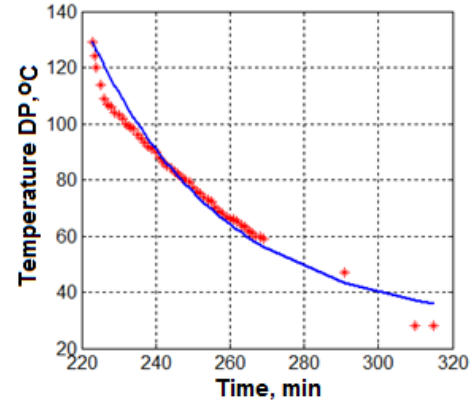


Figure 7. The transitional function of the temperature of the DP during stopping the EBW installation (stars – measured values, continuous – estimated values).

After defining the time constants T , their values are optimized through a minimization utilizing the scanning method of the criterion root-mean-squared error RSME:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i^* - y_i)^2}{n}},$$

where y_i^* and y_i are respectively the experimental and the estimated values using the equations for the corresponding transitional function. The results obtained are presented in table 1.

Figure 7 presents as an example the transitional function of the temperature of the DP during stopping the EBW installation (stars – measured values, continuous – estimated values).

Table 1. Estimated parameters for transitional processes during EBW.

	$y(0)$	k	T	τ	$y(t)$	RMSE
Temperature DP -start	28	108	18.8	49	$k \left[e^{-\frac{t-\tau}{T}} \right]$	3.5241
Temperature DP – stop	28	101	36	223		4.7248
High pressure – start	0.007	0.033	13.5	135	$k \left[e^{-\frac{t-\tau}{T}} \right]$	0.0021
Low pressure - start (before starting the DP)	10	60	1.6	4.5	$k \left[e^{-\frac{t-\tau}{T}} \right]$	2.6845
Low pressure - start (after starting the DP)	1	8	22	112	$k \left[e^{-\frac{t-\tau}{T}} \right]$	0.6132

6. Conclusions

The main aim of developing an ESS for EBW plants is to integrate and organize the knowledge for the EBW processes and plants and to use this knowledge to improve the modeling and control capabilities, their efficiency, adaptability, flexibility and re-configurability.

The ESS is intended for experts and technical staff in manufacturing departments, as well as for learning and training purposes or increasing the qualification in this area of university students or management staff. During the creation and verification of the ESS algorithm, a clarification of strategies and control mechanisms will be conducted so that the ESS could be used for dealing with critical situations.

This paper presents the chosen architecture of the ESS and some aspects of the specification of the functionality of the implemented interactive sub-systems. The automation of the control sub-system of the equipment is considered in more detail. The practical realization of the considered EBW algorithm using PLC will help the implementation of a fully integrated ESS.

Acknowledgements

The work was supported financially by the Bulgarian National Science Fund under contract BIn-5/2009.

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