Integrated control system for electron beam processes

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Abstract. The ISO/IEC 62264 standard is widely used for integration of the business systems of a manufacturer with the corresponding manufacturing control systems based on hierarchical equipment models, functional data and manufacturing operations activity models. In order to achieve the integration of control systems, formal object communication models must be developed, together with manufacturing operations activity models, which coordinate the integration between different levels of control. In this article, the development of integrated control system for electron beam welding process is presented as part of a fully integrated control system of an electron beam plant, including also other additional processes: surface modification, electron beam evaporation, selective melting and electron beam diagnostics.

1. Introduction
The application of the new electron-beam welding (EBW) technologies requires that the EBW equipment be formed into a complex plant, containing highly stabilized power sources and electronic blocks, a reliable and efficient vacuum system and a technological chamber with a high-precision 3D manipulator. They thus become truly software-controlled programmable systems with high efficiency and excellent reproducibility [1]. The highly sophisticated automated processes, including the vacuum pump system and pressure control, the cooling system control, the manipulator control, the processor-based high voltage and emission current control, the electron-beam movement control and its characterization and the PC-based automatic beam power distribution, need to be integrated based on using Manufacturing Operations Management (MOM) systems. The best practices show that MOM systems, when combined with Decision Support Systems (DSSs), can provide the organization with the necessary advanced process control solutions [2-4]. A way to integrate the DSSs (combined with Data Collection and Acquisition, Information Analysis and System Management Agents) with the control and monitoring systems during the operation of EBW is to develop and use integrated control system (ICS) based on MOM.

The ISO/IEC 62264 standard [5-9] supports the development and use of (MOM) systems, providing standard models and terminology for describing the activity models of MOM and interfaces between the business systems of an enterprise and its manufacturing operations and control systems, in order to integrate them. According to the ISO/IEC 62264, the activities in manufacturing operations management are divided into four main areas: production operation management, maintenance

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operations management, quality operations management and inventory operations management. For all areas, a common activity model of eight activities (definition, planning, dispatching, resource provision, implementation, data collection, tracking and analysis) is suggested. To implement a cognitive system, it is necessary to apply an ontological approach for communication between different components and problem solving systems, which can be considered as part of an intelligent information system that integrates them. Ontologies can be used at all stages of the development and functioning of the cognitive system. UML environment will be used to build the cognitive management framework, as well as conceptual models and specifications.

2. Object models for manufacturing operation management
ISO/IEC 62264 [5-9] is a multi-part standard that defines the interfaces and provides standard models and terminology for enterprise (business) and manufacturing-control activities, functions and systems (figure 1 and figure 2). It defines a manufacturing hierarchical model and describes the manufacturing operations management domain and its activities, the interface content and the associated transactions within and between different levels (figure 2).

The basic information structural elements for enterprise application integration are product lifecycle management (PLM), enterprise resource planning (ERP), supply chain management (SCM), customer relationship management (CRM). The manufacturing operations are divided into four groups: production operations, maintenance operations, quality operations and inventory operations. Each operation is presented with an activity model, defined from a set of activities that are required for manufacturing: definition, scheduling dispatching, resource management, execution, data collection, performance analysis and tracking.

![Figure 1. General structure of IEC 62264 standard [10].](image1)

![Figure 2. Functional hierarchy according to IEC 62264-3 [7].](image2)

3. Engineering support system architecture for EBW plant
From a system engineering point of view, the electron-beam plant is a complex system of processes such as electron-beam welding process, surface modification, electron-beam evaporation, selective melting and electron-beam diagnostics, which can be engineered to accomplish specific business and technological objectives.

Figure 3 shows the basic components of an Engineering Support System (ESS) architecture, presented as an UML “use-case” diagram (basic type of UML diagrams) in order to represent knowledge in a form that is either human or computer readable. It is integrated to all levels from the functional hierarchy of the enterprise (figure 4).

The basic use cases of the ESS for EBW plant are: Data Collection and Acquisition (DCA), Information Analysis (IA), Decision Support System (DSS) and System Management (SM).
The DCA subsystem has a direct connection to the EBW plant through the available sensors, which present the actual state of the plant, follow the system behavior and support the data acquisition and archiving.

The IA subsystem includes a component for analytical modeling of the different processes – providing the DSS user with calculated data (weld-geometry parameters, weld defects, temperature distribution, etc.); a component for statistical modeling, quality management and data analysis; components for information modeling; and components supporting optimization processes.

Figure 3. The architecture of ESS for EBW plant as “use-case” diagram.

The SM component involves the definition of requirements and parametric constraints. The DSS implements the results from the DCA, IA and SM components in order to provide the decision makers, the operators and the managers with key information that enables them to make more efficient and consistent decisions.

4. EBW plant domain model
The development of a MOM system is based on the application of an object-oriented approach and the Unified Modeling Language (UML) [11], and uses the ISO/IEC 62264 conforming meta-model, consisting of classes hierarchically composed in three categories of resources (“Personnel”, “Equipment”, and “Material”), “Process Segment” and five main interface models (“Product Definition”, “Production Capability”, “Production Schedule”, “Process Segment Capability” and “Production Performance”). The classes defined in the domain model extend in detail the main meta-classes in “Material Model” and “Equipment Model” by introducing domain information. The domain model is integrated with the meta-model in such a way that all properties and relations, defined in the meta-model, are inherited in the domain model.

Figure 4 represents the electron-beam plant domain equipment model, which is based on the hierarchical equipment meta-model, suggested in ISO/IEC 62264. The EB_Plant represent the “Site” level of the standard hierarchical model. It contains four specific areas of processes: electron-beam welding (EBW), surface modification, electron-beam evaporation, selective melting and diagnostic area. In this paper, the EBW area is only covered. The “Equipment Model” of EBW contains four subclasses: “Manipulator”, “Vacuum System”, “Cooling System” and “Electron-Beam Gun”. The “Manipulator” class has two working regimes (subclasses), depending on the type of manipulator used: “Rotary”- with velocity and rotation angle properties; and a “3D” manipulator, which has x, y and z coordinates. The “Vacuum System” contains three types of pumps as “Actuator_VS” subclasses: two rotary pumps (RP_VS), a turbo-molecular pump (TMP_VS) and a diffusion pump (DP_VS). All of them have one property of Boolean type, defining if the pump is on or off. Other subclasses of the
“Actuator” class in the “Vacuum System” are: an electromagnetic corner valve (EMC_VS) and an electro-pneumatic valve (EP_VS). A thermal binary sensor is placed in the “Vacuum Chamber” for pressure measurement. The “Cooling System” is another unit of the EBW area. It consists of diffusion pump cooling (DP_CS), turbo-molecular pump cooling (TMP_CS) and electron-beam gun cooling (EBG_CS) subclasses. Each of them has one attribute of Boolean type that sends the information on the cooling being on or off. The last unit of the “Equipment Model” is the “Electron-Beam gun” class. This class has his own properties: acceleration voltage, electron-beam current and cathode. Other electron beam properties are: electron-beam power, welding velocity, distance between the main surface of the magnetic lens of the electron gun and the beam-focusing plane, the distance between the main surface of the magnetic lens of the electron gun and the sample surface. The subclass “Deflection System” defines the movement of the electron-beam gun along the welded samples and has the following properties: amplitude, frequency and phase of Signal 1 and Signal 2. The second subclass is the “Focusing System” equipment with focusing-current property, which determines the position of the focus of the electron beam. The last subclass is the Sensor_EBG, based on gas discharge, which has one property for the level of the vacuum pressure in the zone of the electron-beam gun.

![Figure 4. UML based EBW domain equipment model.](image_url)

The “Material Model” contains the material characteristics of the samples that are welded by the EBW process. The welded joints can be from one type of material or of two different (dissimilar) materials – metals or alloys. Figure 5 shows the “Material model” as part of the meta-ontology, based on the ISO/IEC 62264 standard, using “Protégé”. According to the ISO/IEC 62264 standard, the term “material” is a pooled concept for both raw materials, and intermediate and finished products. In general, the different material types and their characteristics are defined by the “Material Class” and “Material Class Property” classes. These can be, for example, welded parts dimensions and the
requirements for zero defects and minimum spiking area in the weld root: weld depth, mean weld width, weld cross-section (area, form) and defects, etc. The specific material and its properties are given through the “Material Definition” and “Material Definition Property” classes. There, the specific raw materials are defined, as for example, the relative strengths of the steel grades, and the end products they produce, as well as their characteristics, such as width, thickness, chemical composition, etc. The “Material Lot” and “Material Sublot” classes are introduced to describe the grouping of materials for scheduling purposes. The “QA Test Result” class includes quality analysis information for the joints formed by the EBW.

5. Conclusions
The development is presented of an integrated control system for electron-beam welding process based on the development of a MOM system, as part of a fully-integrated control system of an electron-beam plant, including also additional processes: surface modification, electron-beam evaporation, selective melting and electron-beam diagnostics. The main aim of the MOM for electron-beam welding (EBW) is to integrate and organize the knowledge for the process and to use this knowledge to improve the modeling and control capabilities, their efficiency, adaptability, flexibility and re-configurability, as well as integration of other technological processes.

References
[1] Koleva E G and Mladenov G M 2011 Practical aspects and applications of electron beam irradiation Experience on electron beam welding eds M R Nemtanu and M Brasoveanu; (Transworld Research Network) chapter 4 95-135
[2] Sheng-Tun L, Huang-Chin H and I-Wei S 2003 Proc. Int. Conf. An ontology based knowledge management system for the metal industry (Budapest 20-24 May 2003)
[3] Bowen J P and Hinchey M G 2005 Ten commandments revisited: a ten-year perspective on the industrial application of formal methods Proc. Int. Conf. Formal Methods for Industrial Critical Systems FMICS’05 (Lisbon 5-6 Sept. 2005)
[4] Koleva E, Batchkova I and Velev K 2008 Engineering support system for modeling and control of the process EBMR of metals Proc. Int. Conf. EBEAM 2008 (electronic) (Reno USA 26-28 Oct. 2008)
[5] *Int. Standard IEC 62264-1* 2013 Enterprise-control system integration Part 1: Models and terminology (Int. Electrotechnical Comm. *(IEC)* Press)

[6] *Int. Standard IEC 62264-2* 2013 Enterprise-control system integration Part 2: Object and attributes for enterprise-control system integration (Int. Electrotechnical Commission *(IEC)* Press)

[7] *Int. Standard IEC 62264-3* 2013 Enterprise-control system integration Part 3: Activity models of manufacturing operation management (Int. Electrotechnical Comm. *(IEC)* Press)

[8] *Int. Standard IEC 62264-4* 2015 Enterprise-control system integration Part 4: Object model attributes for manufacturing operation management (Int. Electrotechnical Comm. *(IEC)* Press)

[9] *Int. Standard IEC 62264-5* 2016 Enterprise-control system integration Part 5: Business to manufacturing transactions (Int. Electrotechnical Comm. *(IEC)* Press)

[10] Clark D 2010 *Invensys presentation standard ISA S95* Invensys operations management

[11] Fowler Martin 2003 *UML Distilled: A Brief Guide to the Standard Object Modeling Language (3rd Edition)* (Addison-Wesley Professional)