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Keywords	Model-based manufacturing - Industry 4.0 - Virtual manufacturing - Additive manufacturing - Virtual reality - Metal forming

Model-Based Manufacturing System Supported by Virtual Technologies in an Industry 4.0 Context

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Abstract. Industry 4.0 concept of the new industrial revolution is based on the application of front-end and base technologies for producing digital solutions. Converging Smart Manufacturing and Smart Products with Big Data and Analytics plays a central role in implementing the I4.0 concept in today's industry. This paper presents the virtual components of the proposed Model-based Manufacturing System and their role in the I4.0 context. Two different industrial cases demonstrate the application and benefits of the MBM approach, which integrates virtual and rapid technologies for the design, analysis and validation of a product and its fabrication processes of sheet metal forming and forging.

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1 Introduction

It is well known how challenging in the industry is to set up a new factory or product, in terms of time, material and human resources. If the whole process is carried out in traditional way, with numerous trial and error attempts in real production and by using production resources, then such approach is not competitive in today's increasingly demanding market. Namely, the I4.0 concept enables companies to adopt and put into practice the implementation of new approaches and techniques for digitalization, cloud computing, the Internet of Things and big data, in order to gain a competitive advantage [1]. New techniques are used to generate virtual and digitized environments to simulate real processes and systems, at all stages of development factory, product, production technology, even virtual quality control and behavioral prediction in real conditions, as well as in other stages of product life cycle. Only after validation of the virtual model it is possible to pilot verified solutions in physical production systems, which are also supported by software for fine-tuning and monitoring. Some examples available in the literature show that it is possible to set up an automotive part production unit in three days, instead of three months as it used to be, through 3D visualization of virtual plant, processes and interaction of workers and machines [2].

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In the future, the fourth industrial revolution, as a result of the introduction of the Internet of Things and Services into manufacturing, will establish global networks with shared production facilities and resources (Cyber-Physical Systems), which will consequently have significant improvements in industrial production, material use, supply chains and improved lives cycle management [3].

Industry 4.0 is conditioned by innovative technological advancements in the areas as listed below. For all of them digitization is common across the entire industrial environment and business activities, starting with business models, products and services, production systems, machines and workers [4, 5]:

1. ICT technology - for digitalization of information at all stages of the product life cycle, both within the company and beyond its facilities.
2. Cyber-physical systems - for monitoring and controlling physical processes and systems, including embedded sensors, robots and additive manufacturing devices [6, 7]
3. Network communications - for internal and external connection of machines, products, systems and people, via internet technology
4. Simulation, modeling and virtualization - for virtual and rapid development of product and manufacturing process, including virtual and augmented reality support for designers and workers
5. Collection of data, analysis and exploitation - for collecting production data and applying techniques for big data analysis.

Despite the fact that Industry 4.0 is considered to be new industry revolution, initiated in the year of 2011, where above mentioned emerging technologies are converging to produce digital solutions, there is still a lack of understanding of how companies should approach their comprehensive adaptation and application in the industry. In order to better understand the adaptation of I4.0 in companies, Frank et al. [8] proposed a conceptual framework for I4.0 within which all technologies are divided into front-end and base technologies. The first group includes technologies that are classified into four pillars: Smart Manufacturing, Smart Products, Smart Supply Chain and Smart Working. The second group is comprised of base technologies containing four elements: Internet of Things, Cloud Services, Big Data and Analytics. A study conducted in a sample of 92 companies found that the implementation of base technologies, especially Big Data and Analytics, is at a very low level, which is a future challenge for companies. It has also shown that Smart Manufacturing plays a central role in the implementation of the I4.0 concept in the industry and is highly integrated with Smart Products technologies.

The term digital twin is often used in the literature for an integrative approach that encompasses the physical product or process, the virtual product or process, and the associated data that link the physical and virtual worlds in the industry [9]. It is applied in all stages of the product life cycle, conceptual and detailed product design, design of production technologies, but also in the control itself. Future research should define the holistic approach of using digital twins in the entire process of product development and production, including the problem of standardization and efficient information flow.

A significant limiting factor in the implementation of the I4.0 concept for companies is the volume of information and data obtained in a cyber-physical system, especially through the application of simulations, modeling and data acquisition from manufacturing. Without a sophisticated approach to data analysis and software-assisted decision-making in the system, one can hardly feel the direct benefits of the I4.0 concept for the company. Therefore, research is focused on the development of Decision Support System based on CPS simulation and optimization [10].

The paper presents the results of applied research of the I4.0 concept carried out in specific industrial cases, which relate to simulations and modelling of production processes, so-called virtual manufacturing, additive manufacturing of products and tools, as well as advanced 3D visualization techniques through the use of systems and software for virtual reality. Their integrative application in rapid product development, validation of the recommended production processes for its manufacturing, optimization of influential process parameters on production outputs, visualization of the design solution is also shown through certain case studies.

2 Virtual Technologies in Model-Based Manufacturing System

Virtual technologies represent a whole set of interconnected engineering technologies for product and process design and are based on the digitization of real objects and the simulation of industrial processes with the acquisition of production data for the setting of input parameters for system modeling [11]. Figure 1 shows the components of a digital model-based manufacturing system for integrated product and process development. Digital model is centrally positioned with all associated information on product and tool design, technological processes, quality control requirements, production, assembly, maintenance conditions, which are generated in the product lifecycle [12].

Reverse engineering (RE), CAD/CAM/CAE (Computer Aided Design/Manufacturing/Engineering), Rapid Prototyping and Tooling (RP/RT), Virtual Manufacturing (VM), Virtual Reality (VR) have been identified as enabling technologies, whose integration within I4.0 context will create the environment where companies will be able to become more innovative and competitive.

Model-based manufacturing (MBM) implies technological merging of CAD/CAM/CAE, as VP&M (Virtual Prototyping and Manufacturing) methods, with RP/RT/RM as PP&M (Physical Prototyping and Manufacturing) methods. Virtual and rapid prototypes obtained in this way can be used for testing the functionality of product or assembly and different concepts in the early stage of design without expensive and long-term trial-and-error attempts in traditional design and production. It creates not only the model of a product/tool, but also the virtual simulation model of production processes in computer environment, known as virtual manufacturing (VM) approach. Based on nonlinear finite element analysis, it enables optimization of key factors of production which directly influence profitability, as an efficient way to test “what if” scenarios, to validate different concepts and optimize related parameters for shop floor. In brief, a capability to “manufacture in the computer” is so powerful tool which reduces the errors to the minimum, cuts the costs and shortens the time of product/tool design, as all modifications are made before the actual manufacturing process. Based on the digital model of a product or tool, it is possible, using specialized CAM software, to obtain an optimal fabrication strategy for CNC machines and to automatically generate NC code for tool movement.

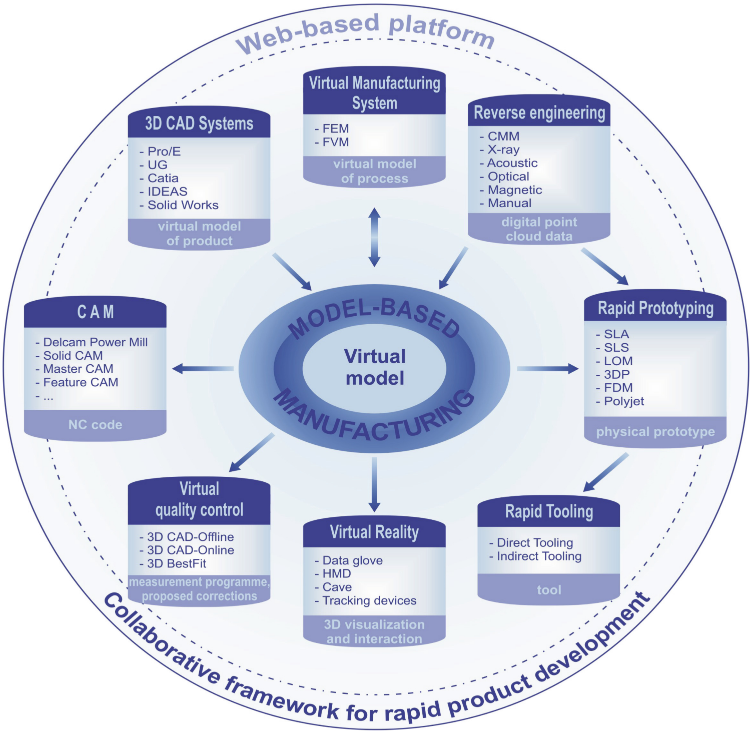

Fig. 1. Virtual technologies and their interconnections [12]

CAD and FEM/FVM models, which are basically digital models, can be obtained in physical form using rapid prototyping technologies and equipment. Modern additive manufacturing systems allow for rapid tooling approaches for production tools and dies. In addition to creating CAD models, 3D model of a product/tool can be also rapidly generated in digital form using reverse engineering, after that remodeled and exported to one of the systems for rapid prototyping/tooling, lately more and more known as Additive Manufacturing.

Model-based manufacturing approach also uses virtual reality (VR) as advanced technology for 3D presentation of model structure, composition and behavior as if it was physically manufactured. VR holds great potential in different engineering applications, such as product design, modelling, shop floor controls, process simulation, manufacturing planning, training, testing and verification thereby preventing mistakes of physical try-outs.

Thanks to the Internet of Things, nowadays it is possible to connect remote teams and companies in a collaborative environment in order to share models and analyze design solutions. All data regarding products, tools and associated manufacturing processes are thus made available in digital form, which can be used for further quality control in the production process, as well as for product life cycle modifications and improvements. If digital models are presented in a 3D environment through equipment and software for Virtual and Augmented Reality, such resources will provide a better understanding of the design solution and of the entire system, for all development professionals, engineers, designers, marketers, managers. It also provides easy maintenance and necessary training when digital resources are embedded in an augmented reality application.

3 The Role of Virtual Technologies in an I4.0 Context

3.1 Additive Manufacturing

Although the I4.0 concept is based on ICT technologies and digital models, Additive Manufacturing (AM), widely known as 3D printing or Rapid Prototyping, is considered to be a vital component that connects virtual environments with physical one. It combines quality and efficient production of customized products with sophisticated shapes and new materials, which are difficult to produce with traditional production. It enables an analysis of the product functionality within the assembly, checking of design solution, ergonomic and other functional testing. Its application exhibited reduction of the lead time for about 60% with respect to the traditional way. Currently, more industrial sectors (automotive, aerospace, biomedical, manufacturing, agriculture, healthcare, etc.) are adopting AM, incorporating greater flexibility and individualization of manufacturing processes, and connecting all processes by IoT [13–15].

An interesting multidisciplinary use case is a combination of electronics and mechanics in designing and rapid manufacturing of sensors and embedded electronics for humanoid robots. Flexible sensors for robots fingers can be designed and fabricated using AM in electronics as well as efficient motors (smaller, simpler, etc.) for achieving more natural robots behavior, for example face mimics [16].

Trends in the development of AM, from the aspect of the I4.0, relate to the development and application of new smart materials, then devices that would produce functional parts, even assemblies/machines, in a single step of fabrication. The third direction of development is related to the design issues limiting the AM process [17].

The choice of AM strategy, which includes parameters such as beam diameter and current, preheat temperature, is critical for the evolution of the microstructure. Predicting deviations in the process of cooling or post-processing and residual stresses using FEM simulations is a significant support for designers and AM operators [18]. The modeling of the AM process is not only a challenge to evaluate the final material properties and quality of the model, but also provides a basis for improving the production process. FEM simulations are very complex with multi-scale and multi-physics endeavor and parameter interaction in complex algorithms [19, 20].

3.2 Virtual Manufacturing

Virtual Manufacturing (VM) is a software-supported system for modelling, simulation and optimization of production processes used in product manufacturing. It generates the same information on the production environment and conditions that can be observed in a real manufacturing system. It enables the reduction of costs and time of product development, early evaluation of product alternatives and its fabrication operations, as well as producibility and affordability, in integrative simultaneous modelling and design of products, processes and resources. Virtual Manufacturing is, in a word, "production in a computer" [21–23].

Process modelling is based on nonlinear FEM (Finite Element Method) or FVM (Final Volume Method) analysis and simulation of all the processes in manufacturing technology of a certain product. Technology simulation makes possible for companies to optimize key factors which directly affect the profitability, like formability, final form and accuracy, level of residual stresses, reliability in exploitation, etc. [24].

Since virtual models of production processes, obtained through virtual manufacturing concept, are very flexible, they allow us to examine the impact of design changes, both product and tools geometry, as well as process parameters, on product quality and production costs. This way, it is possible to perform sensitivity analysis relatively quickly under the conditions of parallel numerical processing, and to identify the areas of the optimized design solution. Moreover, it is possible to predict failure and occurrence of defects in the product, optimal use of production equipment and tools, assessment of tool wear and its life, as well as fracture prevention. The optimal choice of relevant production parameters has positive consequences for reducing time-to-market, production costs, materials and tools, as well as increasing the final quality of the product [21].

Virtual Manufacturing is not only a tool for numerical simulation and optimization of production processes, but also a tool to support the PLM (Product Lifecycle Management) system, for making the right decisions by company management in the early stages of product development [25, 26]. The high complexity of models and analysis, which basically has many different types of data, can lead to problems in the flow of digital information and data. The PDM (Product Data Management) system offers a solution for reliable storage and monitoring of data, so that the right information and data are available in a timely manner and in the right location. Electronic data must be available in different formats, in order to be easily transmitted between subsystems of MBM systems, through appropriate interfaces (Fig. 1).

All this leads to the accumulation of a large amount of data which is not suitable for analysis and decision making. Therefore, recent researches in I4.0 are concerned with a structured and systematic reduction of data gathered during production processes. Systems for the automatic control and integrated consideration of communication in the MBM system with a networked components are being developed [27, 28].

3.3 Virtual and Augmented Reality

Virtual Reality (VR) can be defined as a simulation within which computer graphics are applied to create a realistic-looking world, where the synthetic world is not static but responds in a certain way to user response and modifies in the real-time environment. There is a great need for reality in presentation within a wide range of fields, from education, art, medicine, to virtual production [11, 29].

The implementation of the immersive environment in I4.0 is realized in three ways: Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) [30]. AR can be defined as a computer graphics technique where virtual symbols are superimposed on a real image of the external world [31]. The application of these systems in the industry is especially useful for assembly and maintenance processes, when training and instructions for workers are prepared mainly in the AR technique. For this purpose, expensive VR systems do not need to be used, but for example see-through glasses equipped with camera and small projectors on lenses, or mobile devices like tablets or smartphones. Immersive interfaces and workers' experience are combined to achieve better and more efficient procedures than in the conventional approach.

4 Industrial Application Cases

4.1 MBM Application in Sheet Metal Forming Process

The main objective of the presented case study is to apply an integrated approach to the arbitrarily selected product or product component in the application of multiple virtual technologies in the re-engineering of technological processes in sheet metal forming processes and verification of the proposed tool design. The sheet metal handle, used in the manufacture of different types of cookware, is obtained by processes of blanking, punching, deep drawing and bending of sheet metal. The last bending and closing operation of the handle may be unstable, depending on the workpiece shape in the previous deep drawing/bending operation, and further conditioned by sheet anisotropy.

If the technology development and the tool design are based only on the designer's experience, having numerous physical prototypes of tools and try-outs is inevitable. Virtual product development and optimization of technological processes by virtual manufacturing significantly reduce development time and costs. In established MBM environment based on digital models of the handle and tools, designers can propose and validate several alternatives for product and tools design.

As it is presented in Fig. 2, the applied integrated MBM approach comprised the following technologies [11, 12]:

- Reverse Engineering, for scanning of blank shape and free surfaces of handle, using the multi-sensor coordinate measurement machine WERTH VideoCheck IP 250, which is equipped with three sensors: optical, laser and fiber contact sensor,
- CAD modelling for generating 2D model of sheet blank and 3D models of the handle and tools, based on RE data and created tools for recommended production technology
- Virtual Manufacturing for FEM simulation and verification of proposed technology and tool design by using Simufact.forming software
- Rapid Prototyping for physical verification of obtained digital FE model of handle as VM result, by application of the PolyJet technology and the 3D printer ALARIS 30

- Quality control for comparison between real metallic part and RP model of the handle obtained by FEM simulation, using CMM WERTH and its optical and laser sensors, and
- Virtual Reality for 3D visualization of virtual models in MBM system, as well as for interaction with virtual models; for this purpose VR application was developed by use of the following software and hardware components: Wizard VR Toolkit program, 5DT Data Glove, Wintracker, magnetic 6DOF tracking device.

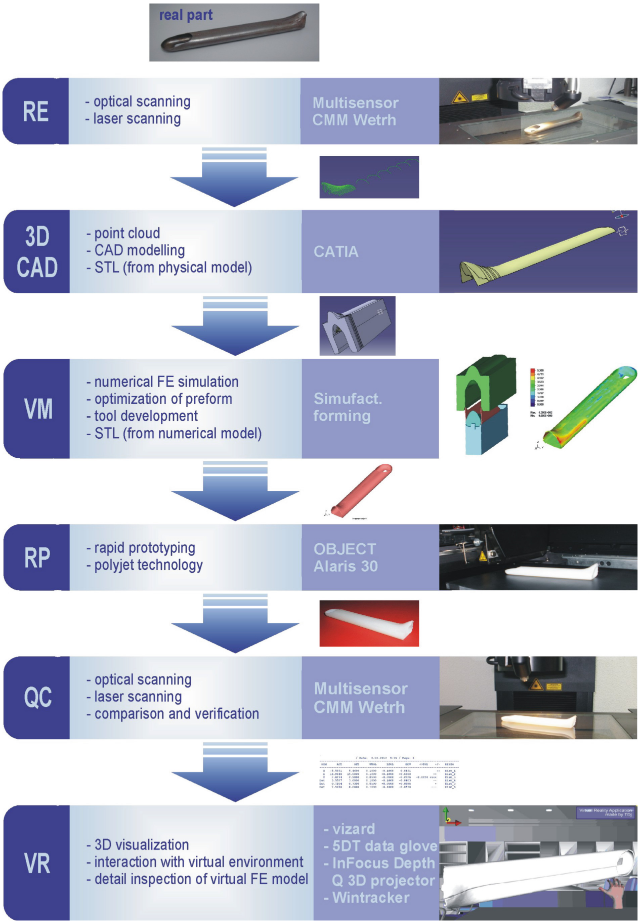

Fig. 2. Integrated MBM approach in sheet metal forming industrial case [12]

Advantages and possibilities of the MBM approach were demonstrated through the presented industrial case, by applying the CAD/CAM/CAE, VM, RP/RM and VR techniques. It was shown that engineering design and development can be very successfully realized, with respect to quality, costs and time savings, by application of the virtual/rapid prototyping/manufacturing technologies.

4.2 MBM Application in Forging Process of the Artificial Hip Stem

Similar industrial case is the development of customized implant of artificial hip, with wide application areas in medicine [32]. The reverse engineering technologies as computed tomography (CT) and magnetic resonance imaging (MRI) have evolved over the years as a beneficial tool in medical diagnostics. Both mentioned scanners generate a certain number of 2D cross-sections (slices) of tissues. There were several proposed techniques to reconstruct 3D objects from 2D DICOM sliced images. By this approach it can be obtained customized shape and dimensions of artificial hip, that is its stem, and it could be generated customized CAD model of hip and its stem.

As it is shown in Fig. 3, CAD model of stem is base for forging technology optimization through numerical simulations (VM) and testing of tool design. After verification of proposed technology, CAM modelling is applied for NC code development for CNC machining of tool components. RP model is used to test prosthesis assembly, and finally coordinate metrology on multi-sensor CMM for certification requirements. The whole cycle in product development, from idea to certified product, that is implant, is covered as total solution for industry application.

Fig. 3. Integrated MBM approach in design of customized implant and its fabrication processes

By identification of geometrical properties of the hip stem applying reverse engineering technology on CT or MGI devices (step 3), it was possible to develop its CAD model using software CATIA and its modules Generative Shape Design and Part Design (step 4). In step 5, the technology of forging a hip stem, of 2CrNiMo18143 alloy, was designed in two operations of preform and final forging. This was preceded by the design of a CAD model of stem forging.

The FVM simulation of both forging operations was implemented in Simufact.-forming software, to validate the tool design and proposed technology, especially the preform shape. After validation of the design solution, a CAM strategy for CNC machining of tools was prepared.

In addition to the VM validation results of the technology, the virtual forged model obtained by FVM simulation was exported as an STL model and additionally printed using PolyJet technology on a 3D ALARIS printer. For the final measurement and verification of dimensions, a multi-sensor CMM WERTH machine was used, especially its optical and laser sensors.

The presented case confirms the benefits of implementing an integrative BMB approach for the development of medical products tailored to the target patient.

5 Conclusions

The paper deals with a set of virtual technologies, whose integration provides the MBM environment for modeling, simulation and analysis of product and its fabrication processes, with the provision of software support for managing product data throughout the life cycle. It enables easy transfer of data from different system components, from design to analysis and verification, and provides a good foundation for virtual engineering approach based on the application of base technologies that are integral part of the I4.0 concept. The MBM environment provides designers and engineers with visualization of products and manufacturing processes and a better understanding of them, leading to quality improvements, shortening the time to market, providing the right design solution without the need for a costly redesign later.

Through the presented case studies, MBM approaches for two industrial examples of different products and technologies have been demonstrated.

The trend of future research is in the application of other physical and cyber components of MBM system to evaluate their limitations and advantages, which should be overcome by an integrative approach. Moreover, standardizing the interface and data form for the exchange of information between different components of the MBM system is a challenge for the future industrial applications of the proposed approach in the I4.0 context.

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