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CHALLENGES, TRENDS AND APPROACHES OF FUTURE RELIABILITY ENGINEERING IN HIGH PRECISION MANUFACTURING PROCESSES

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Abstract
The progress within the development of manufacturing processes leads to complex failure modes and reliability problems within the product life cycle. This fact is valid in the case of mass production of consumer goods, e.g. automobiles, as well as small batch series of industrial goods, e.g. machine tools. Especially micro product platforms with a high amount of derivate and variants are challenging regarding to the planning of high precision manufacturing processes to ensure product reliability.
This paper discusses challenges, trends and approaches of future reliability engineering in planning and realisation of high precision manufacturing processes. It considers e.g. mathematical models for uncertainty quantification, additive manufacturing, hydro micro forming, 3D printing and multivariate process validation models. The paper contains contributions of universities, institutes and original equipment manufacturers of industrial nations: Germany, United Kingdom, Japan, Turkey, Poland and U.S.A.

Keywords:
Challenges, trends, manufacturing planning, manufacturing realisation.

1 INTRODUCTION

The increasing complexity of product functionality and manufacturing process parameters often leads to complex failure modes and reliability problems during the product life cycle. This fact is valid in the case of mass production of consumer goods as well as small batch series of capital/industrial goods. Therefore, the reliability engineering discipline is one of the main spots in future product development and manufacturing processes. This paper shows actual challenges, trends and approaches of future reliability engineering within high precision manufacturing. Base of operations are research activities of international universities, institutes and manufacturers, located in Germany, Japan, Poland, Turkey, United Kingdom and U.S.A. and worked out on the international research platform “Computational Reliability Engineering in Product Development and Manufacturing (CRE)” (cf. section 2). The shown reliability engineering challenges, trends, approaches are integrated in the main activities of the product manufacturing phase (cf. section 3) and explained in section 4. A short summary is given in a summary (cf. section 5).

2 GOAL OF INTERNATIONAL RESEARCH PLATFORM CRE

The goal of the international CRE-platform [1] is the elaboration of challenges, trends and approaches in reliability engineering regarding product and manufacturing process development. The detection of these new activities of reliability engineering leads to the development of future standard reliability methods. Subsequently the application and rollout helps to ensure product reliability regarding the new product generations. Superordinate challenges of product manufacturing planning and techniques are as follows:

- Accomplishment of exponentially increasing product complexity and functionality,
- Handling of increasing product derivatives within value added networks
- Working with new materials and new technologies to ensure product reliability and high precision quality.

3 BASE OF OPERATIONS: PRODUCT LIFE CYCLE

The product life cycle of technical products can be described in four main and eight subordinate phases.

1. Concept phase
    1a. Definition of the product characteristics
    1b. Development of the product concept
2. Development phase
    2a. Construction stages (different prototype levels and finalising of construction)
    2b. Manufacturing planning
3. Production phase
    3a. Start of production (SOP)
    3b. Manufacturing
4. Sale/Usage phase
    4a. Sale of products to the markets
    4b. Usage phase and product observation

In fact, the reliability engineer can influence the product reliability within every main phase of the product life cycle. However, this paper focusses on manufacturing planning and realisation phase.

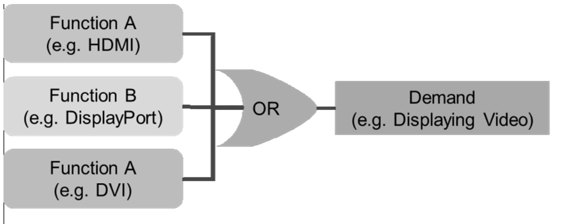
4 CHALLENGES, TRENDS AND APPROACHES OF FUTURE RELIABILITY ENGINEERING

The main activities of reliability engineers are dedicated to the manufacturing phases of the product life cycle (cf. section 3). The subsequently following sections explain challenges, trends and approaches of reliability engineering within the manufacturing planning and realisation phases.

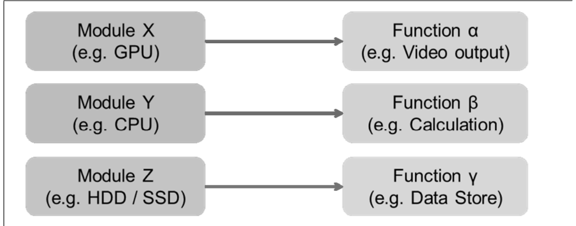
This paper focusses on the manufacturing planning and realisation, considering planning aspects (cf. section 4.1 – 4.4), new materials (cf. section 4.4 and 4.5), new manufacturing technologies (cf. section 4.6 and 4.7) and process validation (cf. section 4.8).

4.1 Product planning phase: Considering module design

Definition of appropriate product design concept at the early phase of design process is essential for preventing unnecessary design change and designing high quality and reliability product. Particularly, the clarification of the important function and designing or selecting modules or components which relate to such function are required. In addition, this function needs to satisfy consumer demand, which many consumers emphasize on. Such demand should be attained by the individual contribution of related modules. In this case - when function or the related module breaks down – the consumer requirements can be supported by the other modules. Furthermore, this means enhancement of product redundancy for attaining demand. Figure 1 (a) illustrates the ideal relationship between demand and function.



(a) Between demand and function (Redundant relation)



(b) Between function and module (One-to-one relation)

Figure1. Ideal relationships between demand and function, and function and module.

In the case of desktop computer's video output, for example, from 3 to 4 outputs such as DisplayPort, HDMI and DVI are usually mounted. Therefore, even though one output is break down, the demand for displaying video is attained by the other outputs as shown in Figure 1 (a). In case that a product equips innovative or advanced functions, the related modules or components sometimes require new structure and new manufacturing technology. At the design and manufacturing stage, high precision engineering and inspection should be applied these innovative modules because they have higher failure possibility compared with the other generalized modules. Figure 1 (b) shows the ideal relation between function and module. In addition, the relationship between function and module is preferable to be one-to-one relationship [2] as shown in Figure 1 (b). Because in case that innovative function is attained by multiple modules, all of such modules should be design by applying precision engineering and this might raise increases of production cost and failure rate. From the above, attaining customer emphasized demand by individual module's contribution and preparing minimum number of modules, which relate to innovative function are essential for designing innovative and failure-robust product. In addition, designer should employ standardized or higher reliable modules for realizing the other functions and avoiding future failure.

4.2 Manufacturing planning phase: Considering maximum tolerable uncertainty

There is a constant demand to improve the precision in manufacturing industries in order to comply with stringent requirements and supply new practical applications that can only work if high-precision manufacturing is available. However, there are still some unavoidable uncertainties that need to be taken into account. Uncertainty can be on different form (point estimates, intervals, vague, or fuzzy). These uncertainties can in theory be reduced by means of implementing new technology and new equipment or collecting more information. These activities are all associated to some costs. It is therefore important to be able to identify which uncertainties need to be reduced and at which level. In other words, it is necessary to identify the maximum level of uncertainty that can be tolerated.

Often engineers design for the worst case but this is also often wasteful over-engineering and inflexible. Probabilistic analyses can instead being used to estimate the risk associated. This task requires uncertainty characterization, the quantification of the uncertainty on the different performance and the accounting of the level of uncertainty in the output due to different level of uncertainty in the input (i.e. sensitivity analysis) [3], see Figure 2.

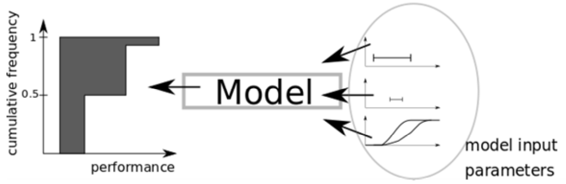


Figure 2. Maximum tolerable uncertainty.

Unfortunately, the results are sometime difficult to translate into crisp design decision. More importantly, such analysis requires a great deal of information about the underlying distribution or their correlations [4]. Instead the concept of back calculation [5] can be adopted to manufacturing at the required level of precision at the minimum cost. For instance, we might to manufacture a product with: a median value defined, 95% of the products are inside specific bounds and none of them with performance worst that a specific level. All these information can be represented by a probability box [5]. Then, based on this representation of the requirements it is possible to "back propagate" the p-box to identify the maximum tolerable uncertainty that guarantee the defined performance, e.g. Figure 2.

4.3 Manufacturing planning phase: Supply chain strategies in the corporate world

One of the recent developments in the corporate world is expanding markets as a result of globalization. Several barriers limiting trade among different countries and

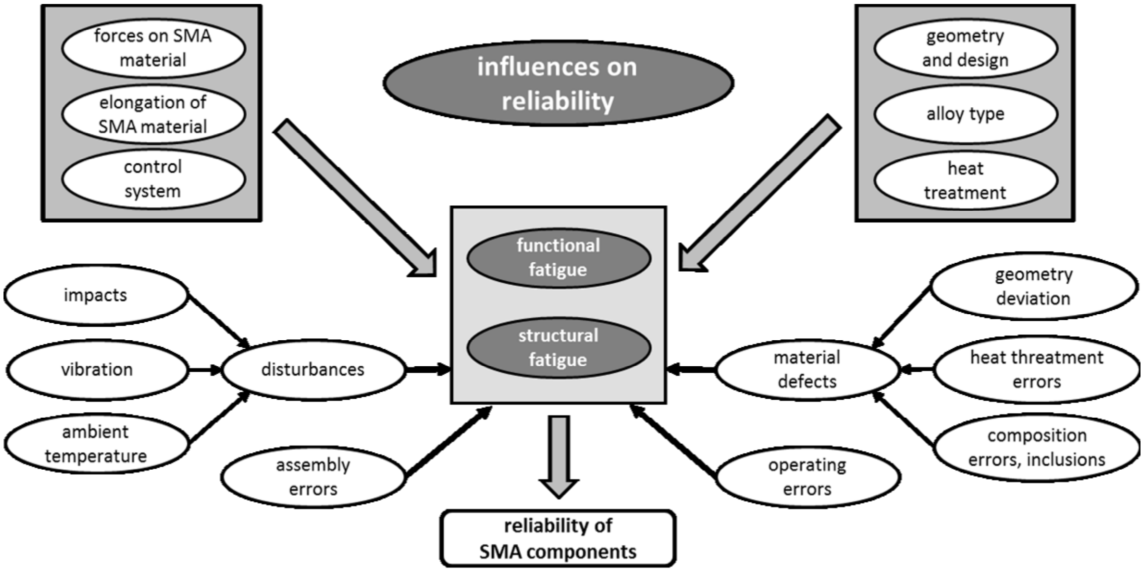
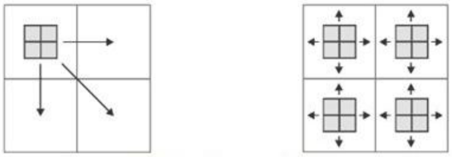
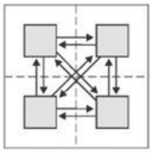


Figure 4. Influencing factors on the reliability of SMA components.

certain blocks of countries started to disappear. Globalization originally facilitated the reach of corporates into different markets worldwide. However, as more corporates started taking advantage of this newly discovered markets, competition among corporates also increased. In the interest of lowering production costs, corporates started shifting their manufacturing facilities to different geographical locations. With this change in the location of manufacturing plants, a new problem surfaced, potential reliability issues with products. In globally concentrated production supply chain strategy, products are manufactured in one facility and distributed worldwide, e.g. Figure 3.



(a) Globally Concentrated SC (b) Host Market SC



(c) Product Specialization SC

(d) Transnational Vertical Integration SC

Figure 3. Possible SC Strategies.

If facilities are located in high labor-cost countries, then corporates tend to use higher level of technology with much higher precision. This definitely increases product reliability. In this case, high machining precision translates to higher product reliability. The corporates may comprise product quality and thus reliability if they move their facility to lower labor-cost countries and choose lower manufacturing technology level. The problem gets only more complicated if corporates other supply chain strategies such as host market production, regional/global product specialization and transnational vertical integration. In host market case, manufacturing technology used in different countries may vary and thus performance of products may not be consistent, e.g. Figure 3. In regional/global product specialization case, similar problems are observed. Finally, in the transnational vertical integration case, bigger quality and product reliability issues may emerge as components may be built in different facilities by using different manufacturing technologies and processing, e.g. Figure 3. The component compatibility may be the key concern if identical manufacturing processes are not used throughout the facilities.

4.4 Manufacturing phase: New materials - Smart memory alloys

The integration of smart materials, especially of shape memory alloys (SMA), into high-volume products represents a major challenge for the production process, e.g. Figure 4 [6, 7]. One reason for this is the sensitivity of the properties of SMAs to the change of process parameters. Even minor differences in the manufacturing process can lead to nonconforming functional properties. Therefore, each individual production step must be closely monitored and validated through test steps. Since today's semi-automated production processes and the manually performed quality tests are very complex, SMA products have not yet been able to become accepted [7, 8]. It must be the goal, to increase the low acceptance in terms of this technology through a repeatable manufacturing process. In addition to a fully automated production, automated quality tests play a decisive role.

Despite the wide range of research, the parameters for an automated large-scale production of SMA have not yet been clarified. In particular, the influence of the ambient temperature and the mechanical load during machining must be investigated in more detail. Springs of shape memory material, for example, which have the same macroscopic dimensions and are produced from the same basic alloy, can nevertheless have different properties.

In terms of SMA, the quality control is very important but also a major challenge. For this reason, new test methods have to be developed [9, 10]. In addition to the geometry, the functional properties, such as force and displacement, but also the quality of the pre-material, must be tested. In addition to the conventional methods, such as tensile or compression tests, newly developed methods based on the measurement of the electrical resistance curve can be an interesting option. The change of the electrical resistance during the phase transformation makes possible to get various information about the SMA raw wire or the finished SMA component. A comparison of the measured curve of the electrical resistance with corresponding nominal curves gives a statement about the quality of the material or of the production process and thus about the reliability of the SMA component, e.g. Figure 4.

4.5 Manufacturing phase: New materials – Polymer composites

Polymer composites are very modern and progressing branch of knowledge and manufacturing. Composite materials were introduced in 1940s but its rapid expansion has started in 1980s thanks to synergy of polymers and reinforcement like: glass, carbon, Kevlar, metal matrix [11]. Although that technique has appeared earlier than 3D printing, composites, especially sandwich composites have many unbeatable advantages over many other engineering materials. High strength, stiffness and law density make them very useful in the structure of means of transport. Advanced applications are visible in almost all kind of technical objects and appliances. Growing market made that technology user friendly and even hand-made composite objects are very popular. That aspect of composite manufacturing is interesting for fans of boats, sail and motor yachts, bikers, automobile and model-making. The problem they face usually is how to achieve high quality composite with limited access to high-tech tools or know-how. Very demanding objects are flying models especially gliders classified as: F3B, F3K, F3J due to requirements like: high speed (up to 500 km/h – dynamic soaring) and acceleration (up to 10G – haul start) and low weight (1kg at 3.7m wing span [glider F5J Plus]). Typical structure of composite wing panel consists of two molded halves (top and bottom) glued together with carbon spar and web shear, e.g. Figure 5 or foam core panel covered with composite skin, e.g. Figure 6 [12].

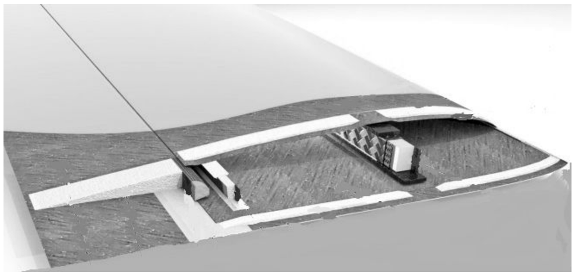


Figure 5. Molded wing panel structure – hollow.

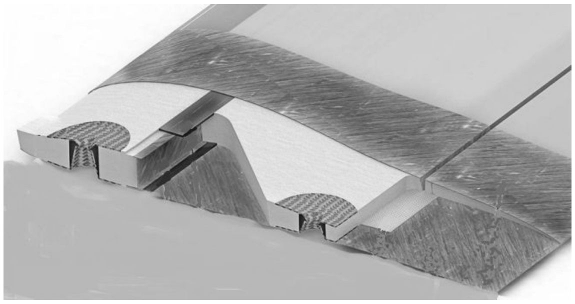


Figure 6. Molded wing panel structure – foam core.

4.6 Manufacturing phase: Micro manufacturing methods

Micro manufacturing methods encompass techniques for the production of miniaturized components as well as of micro-sized geometrical features on conventionally sized products. The individual methods applied in industrial manufacturing can be categorized into micro-electrochemical systems (MEMS)-based processes, such as photolithography, chemical-etching, plating, LIGA, or laser fabrication, etc., and non-MEMS-based techniques such as micro-mechanical machining, micro-EDM, micro-laser machining, micro-forming or micro-injection moulding, etc. [13, 14]. Current applications cover the sectors of communication (e.g. electronic and optical components in cellular phones), mobility (e.g. sensors for distance measuring, stability improvement or signal reception in aerospace or automotive applications), energy (e.g. micro structured surfaces to reduce friction losses), ambient living (e.g. mechatronic systems), health/safety/environment (e.g. devices for medical technology or biotechnology), and production systems (e.g. sensor equipment for tools or robots) with an estimated market of about 25 billion USD in 2019 [15]. Furthermore, some initial research work considered additive manufacturing methods for the manufacture of micro-components, e.g. [16].

Traditional, MEMS-based manufacturing is performed in volume production since many years. But the increasing need for multi-functional and multi-material micro-products/systems as well as for improved production efficiency cannot be coped with these traditional techniques alone [13]. Therefore, conventional, non-MEMS manufacturing technologies were adapted and new technologies developed. However, significant efforts have been, and continue to be, necessary to better understand material behaviours at micro/nano-scale, process capabilities and even manufacturing operational philosophy when scaling down conventional manufacturing processes [13]. In particular, size-effects have to be taken into consideration, which in many cases increase the scattering of process parameters [17], and influence with this crucially production reliability. As an example, Figure 7 shows the influence of material grain size and stress state during forming on the variation of the internal pressure at the occurrence of bursting, experimentally determined for the hydroforming of micro-tubes made from stainless steel and from a platinum alloy with different ratios of grain size to tube wall thickness [18].

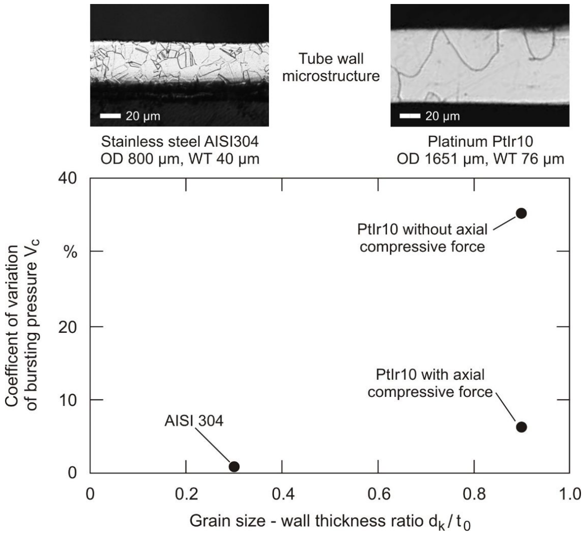


Figure 7. Scattering of process parameters in tube micro-hydroforming [18].

For traditional manufacturing, Condition Based Maintenance (CBM) was developed to ensure a sufficient operational reliability of manufacturing systems [19], with the option to be supported by cloud-based services [20]. However, for micro-manufacturing processes strategies to improve the reliability under the conditions of increased scattering, are predominantly based on case-by-case solution, applying process simulations and methods of Design of Experiments, e.g. [21, 22]. Consequently, additional research on generalised approaches should be a high priority in order to improve the prediction accuracy of reliability in micro-manufacturing processes and its influence on necessary efforts in high volume production.

4.7 Manufacturing phase: Additive manufacturing technologies

Additive manufacturing (also known as 3D printing) is one of the key advanced manufacturing technologies [23] Three-dimensional products are formed through layer-by-layer deposition of material [24]. Small production batches are feasible and economical for additive manufacturing, and since it does not need tooling, production ramp-up time and expenses are reduced [25]. However, common engineering materials such as cast iron and aluminium alloys are not able to be processed with most additive manufacturing technologies [26]. On the other hand [27], state that additive techniques (i.e., direct metal laser sintering additive technique) can be economically convenient and competitive to traditional processes (i.e., traditional high-pressure die-casting) for small to medium batch production of metal parts. Although, the technology is currently being applied in various sectors including fashion, automotive and aerospace in a limited way; it is becoming increasingly popular at end user level. Adoption of the technology at mass scale remains at the conceptual stage [28].

4.8 Manufacturing phase: Multivariate process capability assessment

Manufacturing processes of technically complex products require highly standardised methods to fulfil technical and customer specifications. To accomplish the demanded specifications, various methods, which can be applied at different phases of the product life cycle, have been developed. One of these methods, within the manufacturing phase, is the process capability index (PCI). State-of-the-art is the univariate calculation of the PCI based on the analysis of one product characteristic. With decreasing tolerances and parallel increasing product complexity, industrial state-of-the-art methods – based on one-dimensional PCI – must not be thus sufficient anymore. The multidimensional PCI (MPCI) is one possibility to verify complex manufacturing processes of technical products based on functional important product character sets [29]. Essential approach is the link between PPM and the common state-of-the-art one-dimensional Cpk value: Each Cpk value belongs to a failure probability ppm; e.g. Figure 8 [29].

As a matter of principle, there are three possible approaches to estimate a failure probability with regard to the product characteristic set (multivariate) [30]:

1. The individual estimation of failure probabilities and combination to a multivariate failure probability using Boolean algebra (cf. eq. (1)).

$$\mathrm{P}_{\mathrm{ges}}(t) = 1 - \prod\nolimits_{i=1}^{n} \left(1 - P_{Ci}(t)\right) \tag{1}$$

2. Application of multidimensional distribution models (e.g. normal distribution, cf. equation (2)) based on a set of important product characteristics.

$$\mathrm{F}_{\mathrm{x}}\left(\mathrm{x}_1,\ldots,\mathrm{x}_\mathrm{k}\right) = \frac{1}{\sqrt{(2\pi)^{\mathrm{k}}|\Sigma|}} \exp^{\left(-\frac{1}{2}(\mathrm{x}-\mu)^{\mathrm{T}}\Sigma^{-1}(\mathrm{x}-\mu)\right)} \tag{2}$$

3. Estimation of failure probability based on Monte Carlo simulations.

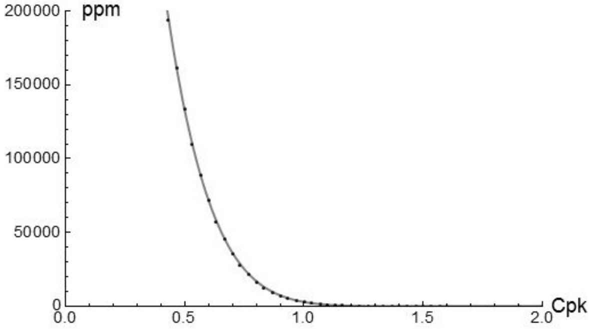


Figure 8. Non-linear regression of the relationship between failure probability ppm and Cpk index [29].

Therefore the failure probability [unit (ppm)] of the multidimensional analysis leads directly to the MPCI and allows a multivariate process validation, as an analogon to the direct conversion of ppm into Cpk [30].

5 SUMMARY AND OUTLOOK

The progress within the development of technical products and manufacturing processes leads to complex failure symptoms modes and reliability problems within the product life cycle. Especially exponential increasing product functionality and new manufacturing technologies leading to the risk of complex failures and damage root courses within the usage phase. This paper discusses challenges, trends and approaches of future reliability engineering within the manufacturing planning and realisation phase. Aspects from planning, organisation, technologies, material and process validation are shown and discussed. These trends in reliability engineering can be part of industrial standard methods to ensure product reliability in a sound way. Future topics of the international CRE-collaboration are the elaboration of a standard method toolbox for reliability engineers.

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7 REFERENCES

[1] ESRA Newsletter, 2016, ESRA Newsletter 03.2016 http://www.esrahomepage.org/newsletter.aspx, access 04.2016.

[2] Suh N.P., 2001, Axiomatic Design Advances and Applications, New York, Oxford University Press.

[3] Patelli E., 2016, COSSAN: A Multidisciplinary Software Suite for Uncertainty Quantification and Risk Management, Handbook of Uncertainty Quantification, Ghanem E., Higdon R., D. and Owhadi, H. (Ed.), Berlin, Springer International Publishing, 1-69.

[4] Patelli E., Beer M. and Kougioumtzoglou I. A., 2014, Editorial: Robust Design - Coping with Hazards Risk

and Uncertainty International Journal Reliability and Safety, Special Issue, 8, 97-313.

[5] Scott F., 2002, Risk Assessment with Uncertain Numbers RAMAS Risk Calc 4.0 Software, CRC Press, ISBN 1566705762.

[6] Miayazaki S., 2012, Shape Memory and Superelastic Alloys - Technologies and Applications, Wood-head Publishing in Materials, ISBN: 1845697073.

[7] Otskuka K., Wayman C.M., 1999, Shape Memory Materials, Cambridge University Press, 07.10.

[8] Czechowicz A., 2012, Adaptive und adaptronische Optimierungen von Formgedächtnisaktorsystemen für Anwendungen im Automobil, Dissertation Ruhr-Universität Bochum, Shaker Verlag, ISBN 978-3-8440-1433-4.

[9] Czechowicz A., 2016, Industrial Safety Systems Using Shape Memory Alloy Actuators, Proc. of ACTUATOR 2016, Bremen, 312-316, ISBN 978-3-933339-26-3.

[10] VDI Richtlinie 2248, 2017, Berlin, Germany, Beuth Verlag.

[11] Palucka T., Bernadette B.V., 2002, Composites Overview. Material Research, http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/composites/Composites_Overview.htm, access 04.2017.

[12] Vladimir’s models, http://f3j.in.ua., access 04.2017.

[13] Qin Y., Brockett A., Ma Y., Razali A., Zhao J., Harrison C., Pan W., Dai X., Loziak D., Micro-manufacturing: research, technology outcomes and development issues, Int. J. Adv. Manuf. Technol., 2010, 47, 821-837.

[14] Fassi I., Shipley D., 2017, Micro-manufacturing technologies and their application, Berlin, Springer Int. Publ., Cham.

[15] Pourabdollahian G., Copani G., 2017, Market Analysis, Technological Foresight, and Business Models for Micro-manufacturing, Micro-manufacturing technologies and their application, Berlin, Springer Int. Publ., Cham.

[16] Scholz S., Mueller T., Plasch M., Limbeck H., Adamietz R., Iseringhausen T., Kimmig D., Dickerhof M., Woegerer C., A modular flexible scalable and reconfigurable system for manufacturing of Microsystems based on additive manufacturing and e-printing, Robotics and Computer-Integrated Manufacturing , 2016, 40, 14–23.

[17] Vollertsen F., 2003, Size effects in manufacturing, Proc. of 1st Colloquium Process Scaling, Bremen, 1-9.

[18] Hartl C., Chlynin A., Radetzky M., 2015, The influence of axial compressive stresses on the formability and scattering of process parameters in micro-hydroforming processes of tubes, Glasgow, Proc. of 4th Int. Conf. on New Forming Technology, 6.-9., 06001-p1-p7.

[19] Bracke S.; Hinz M.; Inoue M.; Patelli E.; Kut S.; Gottschalk H.; Ulutas B.; Hartl Ch.; Mörs P.; Bonnaud P., 2016, Reliability engineering on face of shorten product life cycles: Challenges, technique trends and method approaches to ensure reliability, Glasgow, Proc. of European Safety and Reliability, 25-29.

[20] Babiceanu R.F., Seker R., Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook, Computers in Industry, 2016, 81, 128-137.

[21] Maligno A.R., Whalley D.C., Silberschmidt V.V., Thermal fatigue life estimation and delamination mechanics studies of multilayered MEMS structures, Microelectronics Reliability, 2012, 52, 1665-1678.

[22] Packianather M., Chan F., Griffiths C, Dimov S., Pham D.T., Optimisation of micro injection moulding process through design of experiments, Procedia CIRP, 2013,12, 300-305.

[23] Ford S. J., Minshall T. H. W., 2015, Defining the Research Agenda for 3D Printing-enabled Re-distributed Manufacturing, Advances in Production Management Systems: Innovative Production Management towards Sustainable Growth, edited by S. Umeda, et al., Berlin, Springer, 156–164.

[24] Srai J.S., Harrington T.S., Tiwari M.K., Characteristics of redistributed manufacturing systems: a comparative study of emerging industry supply networks, International Journal of Production Research, 2016, 54, 23, 6936-6955.

[25] Holmström J., Partanen J., Tuomi J., Walter M., Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment, Journal of Manufacturing Technology Management, 21, 2010, 687–697.

[26] Singh R., Singh S., 2017, Additive Manufacturing: An Overview, Reference Module in Materials Science and Materials Engineering.

[27] Atzeni E., Salmi A., Economics of additive manufacturing for end-usable metal parts, International Journal of Advanced Manufacturing Technology, 2012, 62,1147–1155.

[28] Srai J.S., Kumar M., Graham G., Phillips W., Tooze J., Ford F., Beecher P., Raj B., Gregory M., Tiwari M.K., Ravi B., Neely A., Shankar R., Charnley F., Tiwari A., Distributed manufacturing: scope, challenges and opportunities, International Journal of Production Research, 2016, 54, 23, 6917-6935.

[29] Bracke S., Backes B., 2015, Multidimensional failure probabilities based on symmetric and asymmetric product characteristic distribution models within high precision manufacturing processes, Kacem (Hg.) 2016, Proc. of 45th International Conference on Computers, Metz, France.

[30] Bracke S., 2016, Process capability within the manufacturing of complex technical products. Statistical analysis of measurement data. Springer, Berlin, Heidelberg (in German language).