16th IMEKO TC10 Conference
"Testing, Diagnostics & Inspection as a comprehensive value chain for Quality & Safety
Berlin, Germany, on September 3-4, 2019

Integration of Automated Structure Mechanic Analyses into Production Process Simulation

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Abstract – **To produce individual variants of a given product, each variant has to be assessed with respect to their mechanical integrity. This is usually done in the course of product design by assessing all required variants. However, during the lifetime of a product several changes of the existing variants occur or new variants will be created. In this paper a method is described how to integrate and automate the assessment of the mechanical integrity of the product variants directly into the production process by exploiting modern computer methods and automated set-up of state-of-the-art CAE methods. We show this on a demonstrator of a smart factory, that produces disks which can be customized to a large extend. The disks undergo a milling process, which alters the structural properties of the disks. Generally, it cannot be guaranteed upfront that a variant that can be produced is also strong enough to withstand the loads in the application. Therefore, the integrated FEM analyses are computing and assessing the load cases deduced from the use cases of the disks and the loads that occur during milling and handling in the factory. The assessment of the results is done automatically and if positive the production process is started.**

Keywords – **Finite Element Analysis, In-situ assessment, production process.**

I. Introduction

In the product creation process, design, verification and validation of the base product and its variants are usually objectives of the R&D department. The development process is often based on product requirements and takes specifications of all required variants into account. Here, we describe a change in the process that allows for higher development speed since only the basic variants of a product need to be designed upfront. All other variants, as fa as their mechanical integrity is of concern, will be created on demand as part of the production process. The new process will be implemented into the production process of the demonstrator of a smart factory at Fraunhofer IPK in Berlin, that produces customized disks (so-called coasters). In this process a freely designable pattern will be engraved onto the raw disk. For the purpose of this study we assume that not all possible producible patterns are mechanically strong enough to be acceptable for a customer viable product. Consequently, after checking for manufacturability i.e. after creating the control file for the milling process a Finite Element analysis of the new disk geometry will be performed to assure the mechanical integrity of this particular disk variant.

II. State-Of-The-Art

Today's product design processes are often following a sequential approach. Starting from top-level design criteria the product architecture and requirements are defined and the design process will be conducted. The V-Model (Figure 1) illustrates this process with the necessary testing and verification steps.

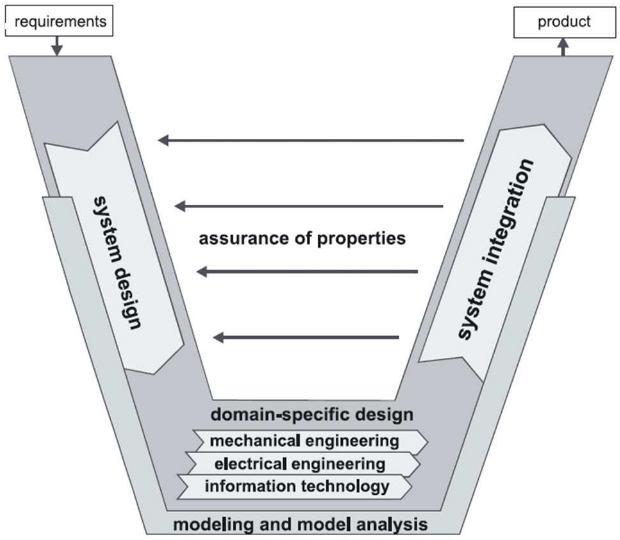

Figure 1: The V-Model according to guideline VDI 2206 [1]

Today, agile methods foster continuous development in smaller steps with integrated testing cycles and enable continuous release cycles of ever changing products [7]. With increasing duration of the overall product life cycle more and more variants will be created in shorter time cycles. Nevertheless, often the technical validity of new variants of an existing product will be done by dedicated teams, sometimes in smaller organisation by the R&D team. This is usually argued by dedicated skills or tools, that have been used during the initial design process. Consequently, the variant or product life cycle management still relies on well distinguished disciplines that act on well-defined boundary conditions e.g. product development requires input from product management or production planning requires input from development.

Stark et. al. [2] described concepts to solve deficits in product development processes for mechatronic products by using data models. In this study, we integrate the structural mechanic assessment of a new variant immediately as part of the production process in a smart factory. Consequently, the variants will be defined and assessed automatically as part of the production process. This becomes possible by modern computer power and sufficient automatization and standardisation of the underlying computational methods, thereby fostering faster turnaround time to create variants.

To assess production, OEE (overall equipment efficiency) is often used [9] despite its major drawback of being too general. OEE is defined as $OEE = AV \cdot PR \cdot QR$ with AV availability (in %), PR productivity (in %) and QR quality rate (in %). Nevertheless, it provides a first indication of the performance of a given production line [8]. Today, plant and process simulations do not include aspects like in-situ structural mechanics assessment of products during production or the assessment of new possible variants, as addressed in this study. However, including this capability into the production process simulation should affect the OEE immediately by increasing all three factors of the OEE. The quality rate can be increased by reducing waste due to producing parts that do not meet the required use-cases or by exposing variants to excessive loads in production. The performance rate can be increased by scheduling the production such, that with altered tools only those variants will be produced that can bear these. And the availability can be increased by reducing commissioning time due to proper scheduling, if for the set-up of the production line is still sufficient for some of the variants.

III. Description Of The Method

For the purpose of this study, the SIEMENS NX tool suite is used to integrate structural mechanics calculation and the assessment of the results into the production process of the demonstrator of a Smart Factory at Fraunhofer IPK [3], [4]. The factory and its digital twin represent a one-piece-flow fabrication line, that produces engraved disks (Figure 2). This allows for a broad variation from mass production down to lot size 1. The pattern can be freely customized via a user interface at the factory. The design will then be engraved by a milling process on the disk(s).

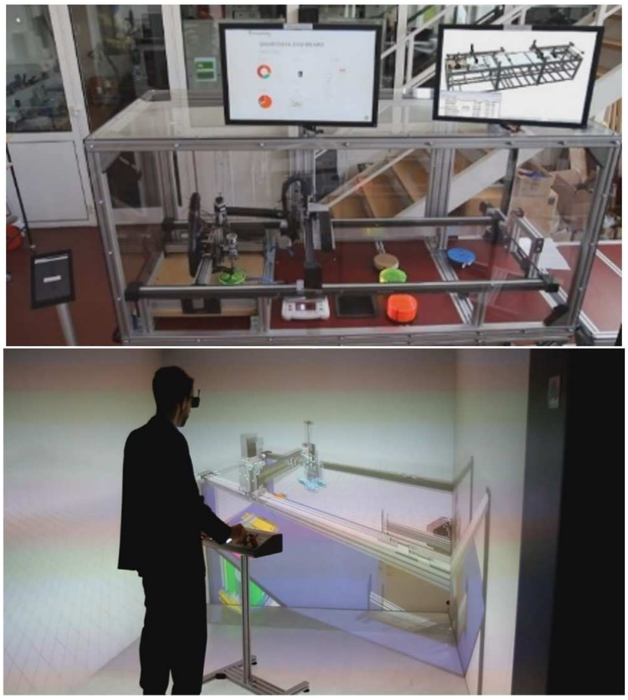

Figure 2: Smart Factory (top) at Fraunhofer IPK and visualisation of its digital twin (bottom).

After defining the design of the disks, the CAD variant is created automatically and the G-code for the milling process is computed. In case this step is successfully completed, the FEM model will be created form the CAD file. Here, it is important to use the same best-practises as they were applied during the design process of the base products in order to ensure reliable and repeatable results. In addition, all changes made to the FEM pre-processing in the future e.g. by exchanging FEM software or using different finite element types or mesh strategies, must be verified and fed back to the design process. Ref. [6] gives good suggestions how to develop and verify such best-practise methods for engineering applications.

The disks are exposed to three types of load cases, illustrated in Figure 3.

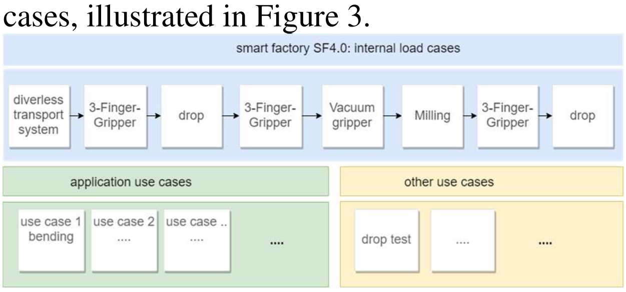

Figure 3: Examples of typical load cases, the product is exposed to.

Firstly, the loads applied during the use of the disk for its intended purpose. Since this demonstration case is fairly simple, the load case is of equal complexity: the use case is defined as a bending load as it may occur, when a disk is bended on a table as it is typical for such coasters (Figure 4). Such use-cases are often defined upfront, the product is verified against it and often the requalification of the product in production also reflect these use cases. If a different use case is desired, the validation cycle must be conducted again. With automated and validated FEM it becomes possible to assess new load cases simply by changing the FEM pre-processing as part of the production line set-up. Figure 4 shows a simulation set-up of a virtual test rig, that may be the digital counterpart of a real physical test rig. The test object is supported by the lower left clamp and a round support underneath the disk. The load is applied via a moving bar on the top right with specified force. The material of the provisions is steel.

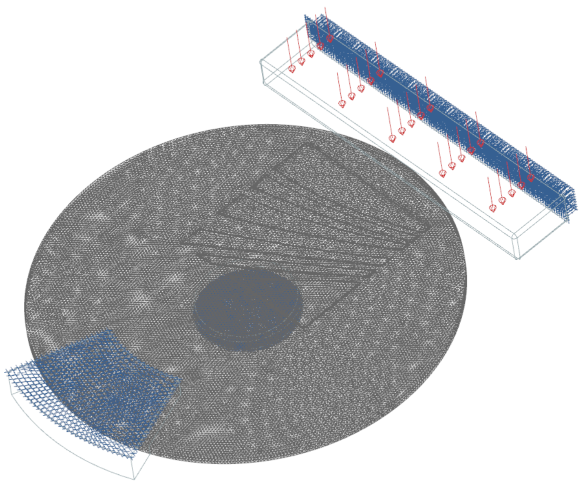

Figure 4: Mesh and applied loads of a disk variant with a typical pattern to be engraved. Load applied by a moving bar and disk supported on top and bottom by a fixed sector provision and a round support, respectively.

The second type of loads applied to the product are those loads that occur during the production process itself. In the Smart Factory, the disks are exposed to the following loads: the disks are transported by a driverless system to their storage place. A single blank disk is picked-up by a mechanical 3-finger gripper and dropped onto an electronic scale. In case the disk mass is within the correct range it is picked-up again and transported to the milling process. Here, it is fixed by a vacuum device during milling thereafter picked up again and finally dropped to its end station.

These load types are different in character and their magnitude may change over lifetime. E.g. the gripper force or the suction pressure of the fixture may change due to wear. Since these factors are measurable by sensors, the actual values can be used to perform the structural mechanic calculation. The order of load cases to which the disks are exposed is of importance as well. This becomes important when changing the order of the process steps itself or when exchanging e.g. one fixture mechanisms. Consequently, the FEM assessment procedure needs to be adopt accordingly.

The third type are loads that may occur by external events like dropping a package during transportation. For the purpose of this study, we exclude these load cases because they can be treated similar to the first type of load cases.

It is desirable to have fast response time of the results the FEM calculations. This allows for just-in-time production of lot-size 1 variants. However, it is thought that under realistic conditions variable quantities are more important. Therefore, a proper planning of the production, based on respective process simulations allow for some calculation and response time of this load calculations. Nevertheless, fast turnaround time of the computation process can be get by leveraging cloud-based computation. In this study, the actual FEM calculations were performed outside of the smart factory using the network of the Fraunhofer Simulation Alliance.

As described above, the automated structural assessment procedure reflects (external) use cases and covers internal loads created by the production process itself. Since the parameters of latter can always be deduced from the actual status of the factory (e.g. from sensor data) the calculation and assessment can be done with a reduced amount of safety factors. Every set of calculation becomes unique and should be added to the data set of the digital twin of the product [5].

The data set for the structural mechanic assessment is therefore unique for each variant and if desired for every individual part. The results of the FEM may be either positive, meaning the design passes the structural mechanic criteria and the factory starts producing the disks or negative. In this case the user wants to use the results to modify the design of reject it depending on the particular results. Therefore, the FEM data are made available to be used more detailed investigation.

A negative assessment does not necessarily mean that this variant will not be produced. In case the internal loads due to the production process are higher than those of the actual use cases, the factory setup may be changed directly in order to avoid pre-damages on the product. Alternatively, a load reduction on the disks may be possible simply by exploiting the natural degradation of the factory components towards e.g. lower clamping forces by using smart planning processes. In these scenarios, more robust variants will be produced earlier to the more delicate variants. A sufficient process simulation should then include the results and methods of the FEM assessments as well.

In this study we focus on one internal load cases and the particular use case illustrated in Figure 4.

IV. Results And Discussions

For this study, the gripping of the disk after milling and the bending (Figure 4) have been selected as internal load case and as application case, respectively. Also, it is assumed that the calculation set-up (i.e. grid size and type, software, etc.) is taken firstly from best practice from development and product qualification. Here, we used PPM as disk material and ABS as gripper material. The disk mesh has 234000 elements. Siemens NX has been used to perform the Finite Element computation and to control the entire automated calculation.

In the first step, the geometry of the variant is processed and handed over to the preprocessor of

NX. The inner load case is then set up and computed. In this study, the three-finger ABS gripper is modelled as three blocks that each apply a specified force of 43.33N in radial direction, the PMMA disk. (Fig. 5). The values of the radial forces are taken from the gripper specifications.

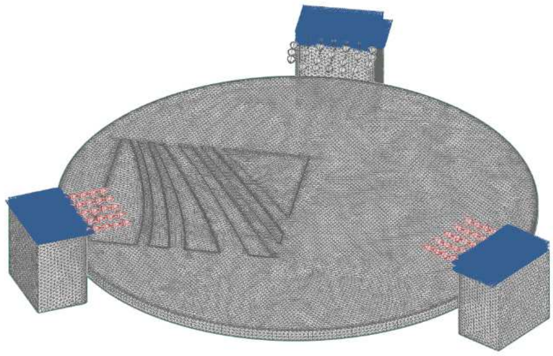

Figure 5: Disk and three-finger gripper as modelled in the FE-calculation. Gripper fingers apply force radially to the disk.

The rule-based automatic pre-processing results in an input file for the actual FEM solver. This input file can be sent to any computer that has a solver license and it powerful enough to perform the computation. A convenient way is to sent it to a cloud service provider to perform the computation and transfer just the acceptance criteria back to the factory. This minimized network load and circumvents the need for hosting an own software.

As assessment criteria the maximum stresses in the all components involved, i.e. the three gripper fingers and the disk itself are used. This allows for assessing the disk for the processing in the factory and also the actual status of the gripper since e.g. material ageing models can be included to the FE-model of the gripper in order to allow for life expectancy assessment and alike of this plant component. Clearly, the entire plant could be simulated by including more and more components and their behavior to the Finite-Element model. In a later study it is planned to elaborate more on this topic to assess efforts vs. benefit of such attempts.

At the moment, the assessment is based on comparing the computed maximum stress with the maximum allowable value for each component involved in the set-up. E.g. in case the maximum calculated stress value of the disk exposed to the loads of the external use-case exceeds the allowable value (e.g. obtained in experiments during the product development or simply taken from a material database) this variant will be rejected as not suited and no production will be granted.

Also, if the computation of the internal load cases yields negative results for one or more factory components, e.g. the gripper is not able to carry the disk due to its material shortcomings, production for this particular variant will not be started, however the negative feedback will be given to schedule maintenance. Figure 6 shows the resulting von Mises stresses of the configuration. The maximum stress value of about 3.1 MPa occur at the gripper finger close to the engravement, however they are very well below of the critical limits of either the disk (73 MPa) or the gripper (35 MPa).

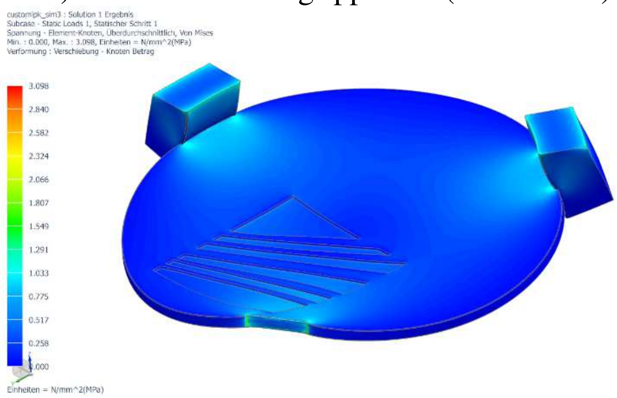

Figure 6: Von Mises stresses of the clamped disk under load. Note: third gripper finger not show in this post-processing picture and displacement five times enhanced for illustration.

Figure 7 shows the results of the application use case as it occurs in the virtual test rig set-up discussed in Figure 4. The maximum stress value is computed as 37.6 MPa, which is of the order of magnitude of the said max. limit for this disk material. The control script automatically picks the maximum value and compares it with the allowable value and grants or rejects production. Here, production will be granted. In case of rejection, the results can be studies further and serve as input for a feedback-to-design process for future product developments. The same is true for changing load cases either due to new demands on the product yielding new test procedures or due to new production methods yielding to new load cases during production of the disks.

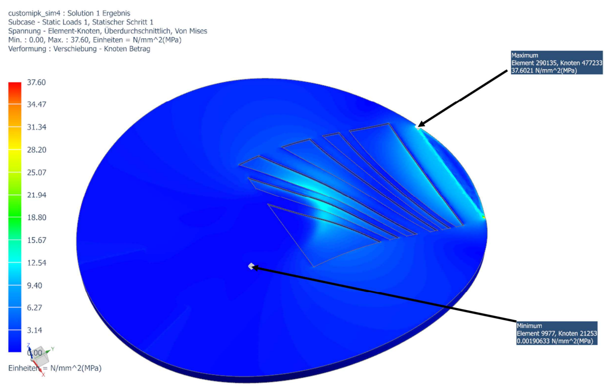

Figure 7: Von Mises stresses of the bended disk under application loads. Note: the provisions of the virtual test-rig are not shown and the displacement is five time enhanced for illustration.

Both categories can be assessed beforehand and the learnings can be fed back to design of the product and/or the production plant.

V. Conclusions And Outlook

The automated set-up of FEM calculations for product variants allows an assessment of the mechanical integrity during the variant production. In order to do so, the best-practice methods for the FEM calculation have to be applied to the variant calculation, too. The pre- and post-processing is set-up, controlled and assessed automatically while the calculation itself may be performed externally in e.g. cloud environment. After the positive assessment of both use case and internal machine loads onto the product, the production is started.

A negative assessment does not necessarily mean that this variant will not be produced. In case the internal loads due to the production process are higher than those of the actual use cases, the factory set-up may be changed in order to avoid pre-damages on the product.

In the next steps, the numerical results and the FEM setup will be part of the digital twin of the individual product. Furthermore, an individual treatment of the product and machine deviations will be taken into account. Also, possible next steps are the enhance the speed of the computation further.

In the future we will use randomly created customization pattern in addition to historic results to train a neural network and use those answers instead of direct FEM calculations.

VI. Acknowledgments

The authors would like to thank Lennert Pannitz for conducting the FEM analyses and integrating it into the workflow of the smart factory.

References

[1] **VDI Verein Deutscher Ingenieure e.V., VDI 2206:** Entwicklungsmethodik für mechatronische Systeme, 2004.

[2] **Stark, R., Beier, G., Figge, A., Wöhler, T.:** Cross-Domain Dependency Modelling - How to achieve consistent System Models with Tool Support. In: Proceedings EuSEC 2010 - European Systems Engineering Conference (CD-ROM), Stockholm, Sweden, 23.-26.05.2010

[3] **Damerau, T.; Vorsatz, T.**: Demozelle Smarte Fabrik 4.0, *FUTUR Ausgabe 2, 2016.*

[4] **ProSTEP iViP Association**: Production Lifecycle Information Management; White Paper, 2019

[5] **Stark, R., Damerau, T.:** Digital Twin. In: The International Academy for Production Engineering, Chatti S., Laperrière L., Reinhart G., Tolio, T. (eds) CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg, in print

[6] **Hellen, T. K.; Becker, A.A.**: Finite Element Analysis for Engineers - A Primer, NAFEMS, Hardback 438 pages, Dec. 2013

[7] **Scaled Agile, Inc.:** SAFe 4.6 Introduction, White Paper, November 2018

[8] **Fuchs, F.:** Key Performance Indicators in Automated Production, Integrationsaspekte der Simulation: Technik, Organisation und Personal; Gert Zülch & Patricia Stock (Hrsg.); Karlsruhe, KIT Scientific Publishing 2010

[9] **Koschnitzke, T.**: Kontinuierliche Verbesserung mit Total Productive Management. Ziele und Kennzahlen für Verbesserungsprogramme in der Produktion. Hamburg: Diplomica Verlag GmbH, 2008