
CIRP ANNALS 2012
Manufacturing Technology
Annals of the International Academy for Production Engineering
Annales du Collège International pour la Recherche en Productique
Berichte der Internationale Akademie für Produktionstechnik
Volume 61/1 • 2012
CIRP
ELSEVIER

CIRP Annals - Manufacturing Technology 61 (2012) 163–166

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Integration of manufacturing-induced properties in product design

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ARTICLE INFO

Keywords:
Forming
Product development
Manufacturing-induced properties

ABSTRACT

Guidelines of the design for manufacturability (DfM) hardly regard neither specific positive effects nor additional functional convenience achievable by specific manufacturing technologies. Consequently, opportunities for design quality improvements are wasted. The paper introduces a new approach in terms of connecting methods of product design, mathematical optimization, process planning and forming technologies, which inherently change material properties of the workpiece. By providing manufacturing-induced properties at an early stage of product design additional functionality can be generated and product complexity reduced. Due to the algorithmic approach design solutions based on different manufacturing technologies can be efficiently compared in mature development stages.

1. Introduction

New products have to be innovative, aligned to customer needs and stand out from competitive products. Additionally, a distinctive cost advantage is requested. One possibility to approach this challenge is to incorporate characteristic advantages and potentials of the used manufacturing technologies into the product design. Thus, functional benefits that upgrade a new product can be achieved. Furthermore, part complexity can be reduced.

In order to take advantage of the full technological potentials applicable product development methods are necessary. A new approach is described in this paper. It includes methods of discrete and nonlinear optimization and exploits these potentials by integrating the systematic utilization of manufacturing-induced properties into product design. The application is shown for the case of forming technologies. In this group of manufacturing technologies properties of workpieces are extensively affected by plastic deformation and tribological phenomena.

2. Potentials in given product development processes

The early phases of the product development (PD) process, especially clarification of the task and conceptual design, are essential for the efficiency of the development process and the level of product innovation. Important decisions are made which substantially influence the functionality, costs and quality of the product. Approved approaches like VDI 2221 [1] and VDI 2222 [2] recommend a stepwise, iterative procedure and result in intensive early phases of the PD-process [3] as a basis for innovative and successful products (Fig. 1(a)).

The conventional development of design solutions is strongly influenced by manual actions and decisions. Experience, intuition and acquired knowledge from previously solved problems are used to take decisions. In general, finding the optimal solutions by experience-based approaches requires huge efforts though optimality cannot be guaranteed.

Product properties are influenced significantly during manufacturing processes. Therefore, it seems attractive to take advantage of the so called manufacturing-induced product properties. In the case of metal forming, properties of manufactured components are affected by the ruling mechanisms of plastic deformation. These result in a shifting of, e.g. hardness, surface roughness and microstructural conditions. Hardness of material is locally influenced by every kind of cold forming process. Caused by, e.g. dislocation movements or twinning characteristic values of strength rise. The effect of hardness increase in the forming zone is described in [4] for ironing, in [5] for bending and in [6,7] for linear flow splitting. During forming processes the surface structure of workpieces is often also substantially affected. Depending on, e.g. contact normal and shear stresses, state of lubrication, tool roughness, relative velocity, temperature and surface enlargement the product surface is modified. The modifications can result in surface smoothening, roughening or structuring as well as a hardness increase. These effects have been observed in processes like cold forging [8], shot peen forming [9] and ironing [10]. Forming processes can also induce grain structure modifications. Especially severe plastic deformation processes like linear flow splitting [6], [7], linear bend splitting [11] or equal channel angular pressing [12] lead to fine grains with dimensions less than 1 μm. These refinements provoke marked changes in hardness, ductility and fatigue strength.

Existing PD-approaches incorporate properties achievable with specific manufacturing technologies only in the embodiment and detail design phases, i.e. in later stages of the PD-process. Here the manufacturing technology is considered in terms of rules and guidelines [13,14]. These guidelines place emphasis on issues like process limits, advantageous part geometries, machine capabilities, energy consumption as well as ecological aspects. They focus on technology specific rules for workpieces that are intended to be manufactured by, e.g. welding, casting, deep-drawing or bending.

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0007-8506/$ – see front matter © 2012 CIRP.
http://dx.doi.org/10.1016/j.cirp.2012.03.041

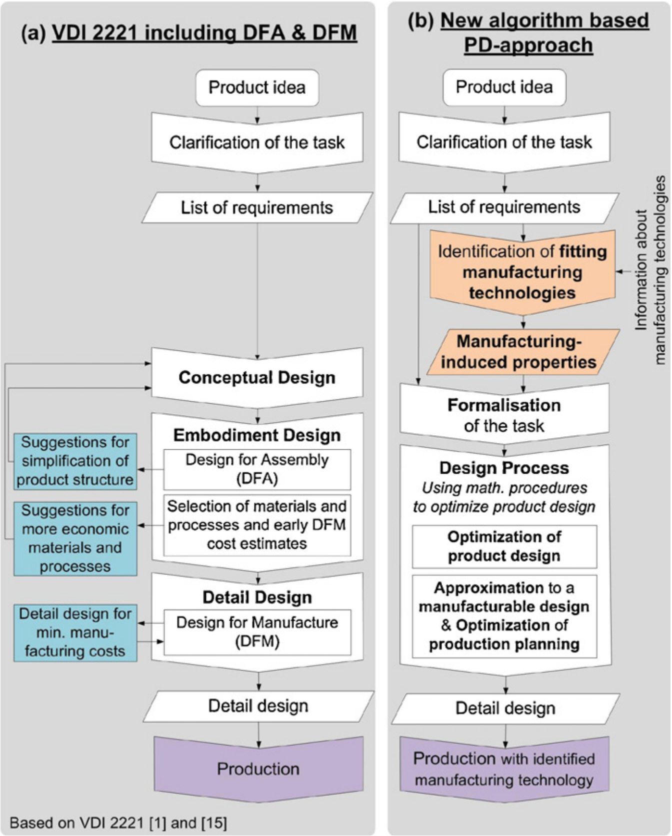

Fig. 1. Conventional PD-process (a), new algorithm based PD-approach (b).

Such kinds of guidelines are summarized in different approaches of “Design for X” (DfX) like “Design for Manufacturing” (DfM) [15] and “Design for Forming” [16]. As shown in Fig. 1(a), DfM affects only the detail design of products. They are irrelevant in the process of determining and generating the conceptual and embodiment design.

Within the approach of axiomatic design manufacturing technologies are considered within the last of four domains. After the design parameters (DPs) are chosen, appropriate manufacturing issues are considered in terms of process variables (PVs). The axiomatic design methodology also includes iterations. This enables the designer to redo the entire design, including modifications of functional requirements (FRs) and design parameters [17]. Requirements can affect the selection of manufacturing technologies, especially if specific tolerances, surface parameters, materials or part dimensions have to be met. These requirements reduce the space of possible solutions but they do not reveal opportunities resulting from the manufacturing-induced properties. This shows the necessity for a new PD approach that considers the manufacturing-induced properties at an early stage of design and thereby enables the generation of optimized products with additional functional benefits and reduced complexity.

3. New algorithm based approach

The newly proposed PD-approach is shown in Fig. 1(b). After the clarification of the task and the listing of requirements appropriate manufacturing technologies can be identified. This identification of fitting technologies is based on existing knowledge about manufacturing technologies and their characteristic manufacturing-induced properties.

Since the following design process has to be carried out for every single fitting manufacturing technology a straightforward and efficient design process is crucial. Additionally, it should be guaranteed that the optimal design solution for each identified fitting manufacturing technology is determined.

In order to fulfil these requirements mathematical optimization algorithms are used. Their application requires a mathematical formulation of the development task. Therefore, the list of requirements is transferred into constraints and objectives [18]. The independent properties [19] or design variables which are directly influenced by the designer during the conventional PD-process serve as optimization variables. Solving this optimization problem yields an optimum product design under the identified constraints and the exploitation of the manufacturing-induced product properties. For the purpose of complexity reduction constraints resulting from the manufacturing technologies are neglected in this step.

In the next step the manufacturing feasibility of the determined product design has to be ensured. Therefore the design best fitting to the optimized solution but also producible with the identified manufacturing technology is sought after. The search operation represents also an optimization problem.

Finally, in order to estimate necessary resources and costs the process planning for the manufacturable and optimized design has to be carried out. This task can again be solved with mathematical optimization algorithms.

In order to compare solutions based on other manufacturing technologies the PD-approach has to be repeated with the according manufacturing-induced properties and constraints. Since the PD-approach in these three steps is algorithm based, the procedure is highly efficient and different solutions based on alternative manufacturing technologies can be compared on a mature level.

A detailed exemplification of this approach is given in the following case study.

4. Case study: development of a multi-functional linear guide

A linear guide made of steel in a robust design with a minimized number of components is sought after. Besides high stiffness the rail has to offer the functions of clamping the guide slide and detecting its position discretely. Small energy consumption for the linear movement is demanded.

4.1. Identifying requirements

First, essential requirements to the product have to be acquired and restrictions for the following PD-process have to be derived. The required main function of the system is guiding a slide on a rail using rolling elements. Furthermore, forces and momentums on the slide have to be compensated in all directions. In terms of stiffness only a specific deflection of the guide tracks under a predefined load case is acceptable. Therefore the contact surfaces are defined regarding their position, length and their angle relative to each other.

The additional features ‘applying clamping force’ and ‘detecting discrete position’ add up to additional restrictions. For the application of the clamping force the following mechanism is selected: a flag – attached to the carriage – runs through a gap between two closed pressure chambers. With the aid of pressure generation side walls of the pressure chambers are displaced outwards and used for the clamping of the slide by friction forces (Fig. 2) [18].

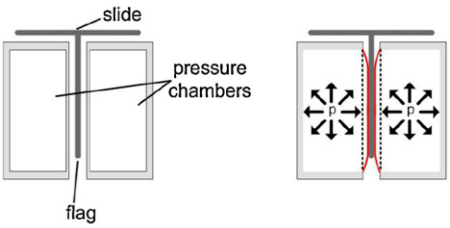

Fig. 2. The principle of clamping force generation.

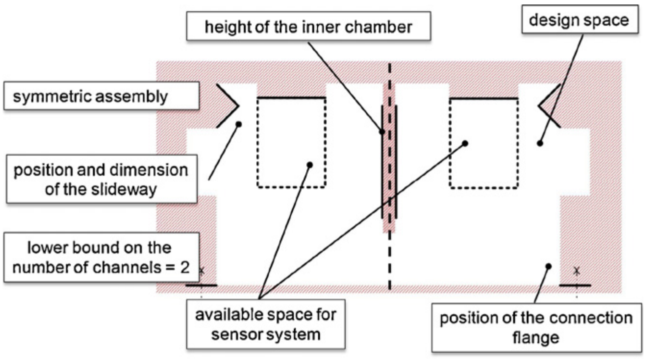

Fig. 3. Summary of restrictions.

Fulfilment of the requirements concerning amount of clamping force and reaction time of the clamping mechanism depends on the dimensions of the flag and the chambers. Therefore maximum volume, minimum height and width of the chambers, the gap width between the two pressure chambers, thickness of the flag, the friction coefficient as well as the deflection of each chamber wall trigger the achievable clamping force. To integrate these relations into the subsequent mathematical optimization process a mathematical model has to be built up [18].

In order to materialize the function 'detecting discrete position' inductive sensors located inside the rail are chosen as basic principle. The resulting restrictions are the minimal dimensions of the chamber and the maximum distance between sensor and the slide. Restrictions concerning position and dimensions of the junctions are derived from mounting requirements. All relevant restrictions for the following design process are assorted in Fig. 3.

4.2. Integration of manufacturing-induced properties

Based on the acquired requirements the technologies of linear flow splitting and linear bend splitting are identified as suitable for the production of the linear guide. They enable the manufacturing of bifurcations in integral style at the edge of sheet material as well as in the sheet middle within a continuous process [6,11]. A subsequent roll-forming process allows the manufacturing of multi chambered profiles in integral style [20]. Due to the mechanisms of severe plastic deformation an ultra-fine grained structure develops during the forming process at the bifurcations' surface. It can be characterized by an increased hardness and ductile behaviour at the same time [7]. These properties, going along with an increased rolling and sliding contact fatigue strength, predestine the linear flow split flanges to be used as rolling contact surfaces [21]. This is accomplished by defining the flange areas of the profile as rolling contact areas during a very early stage of product development, which comprises the position, length and opening angle of the flanges. Herewith the integration of manufacturing-induced properties enables the utilization of all the potentials provided by the applied forming process. Neither any special kind of material has to be implemented into the guiding area nor does any process of hardening have to be integrated into the process of manufacturing. In the same way free flanges are defined in order to realize the connection of the guiding rail and the basis.

4.3. Transferring information into the mathematical optimization

Due to a formalized and analytic description of all restrictions concerning design space, dimensions and wall thicknesses of chambers as well as position and dimensions of functional elements, the design task can be transferred into a mathematical optimization problem. The above mentioned potentials given by the manufacturing process are integral part of the further design process. Due to the algorithmic finding of solutions by mathematical optimization, variants are generated, which fulfil the given constraints and ensure an optimum target achievement.

4.4. Computing the optimal profile using mathematical optimization procedures

A mathematical model is set up which is solved by methods from discrete and nonlinear optimization. Here the design variables **u** such as the length and width of the channels are implemented in form of continuous variables. The restrictions on the geometry are represented by linear and nonlinear constraints. Requested properties of the product such as low weight of the guide or low deflection are encoded in the objective function J of the model, which depends on the state **y**. The model can be summarized as

$$\begin{array}{r|l} \min J(\boldsymbol{y},\boldsymbol{u}) & y \in Y(\boldsymbol{u}) \\ C(\boldsymbol{y},\boldsymbol{u}) = 0 & u \in U_{ad} \end{array}$$

where $Y(\mathbf{u})$ describes the state space, and thus contains the constraints. The behaviour of the product is expressed as a partial differential equation (PDE) constraint $C(\mathbf{y},\mathbf{u}) = 0$. The design has to be chosen from U_{ad}, the space of admissible designs. The solution process necessitates topological decisions, for instance on the position of the channels, as well as geometrical decisions such as the widths of the sheet metal. So far, the optimization algorithms known from the literature concentrate on just one of the aspects, i.e. either topology or geometry optimization, see [22]. Therefore a new method integrating both topological and geometrical considerations in one algorithm is developed: The underlying idea is to use a branch-and-bound approach, where in each node of the branch-and-bound tree a nonlinear optimization problem has to be solved. The nodes of the tree represent certain topology decisions. In the root node of the tree, only those areas are fixed that are restricted due to the application of the linear guide. For instance, above the sensor no sheet may be placed to ensure their functionality. Every step down in the tree fixes at least one channel. Once all channels are fixed, the solution of the nonlinear problem located in the corresponding leaf of the tree represents a possible geometry of the linear guide. Observing all restrictions from the PD-process, the optimal profile determined by the mathematical optimization procedure is depicted in Fig. 4(a).

4.5. Transformation into a manufacturable design

Manufacturing of a profile with the cross section shown in Fig. 4(a) is beyond today's available capabilities of linear flow and bend splitting technologies. In order to achieve manufacturability the number of bifurcations has to be reduced.

Therefore, the objective is minimizing the difference of the geometry of the optimized and the manufacturable profile under the restriction that the number of bifurcations does not exceed a predefined number. This task can be transferred into a mathematical optimization problem. In this case study the procedure is carried out with a knowledge-based approach. This results in a cross section geometry shown in Fig. 4(b).

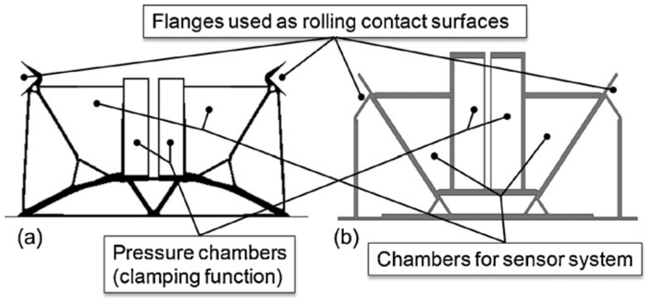

Fig. 4. Optimized profile geometry (a), adapted profile geometry (b).

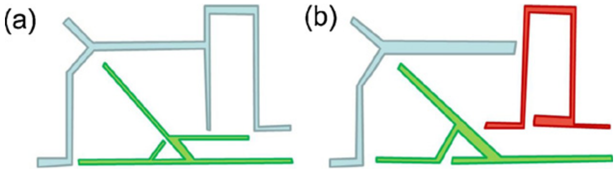

Fig. 5. Unrolling consisting of two (a) and three parts (b).

4.6. Optimization of production planning

Given a profile geometry, it remains to determine an unrolling, i.e. a procedure to produce the profile without violating manufacturing restrictions. Hereby, bifurcation loci have to be identified as splitting, joining or bending points. The determined optimal profile geometry (Fig. 4(b)) is approximated as close as possible. The objective can be written as

$$\min|G(\boldsymbol{U}_{opt}, \boldsymbol{\rho}_{opt}) - G(\boldsymbol{U}_{manu}, \boldsymbol{\rho}_{manu})|,$$

where $\mathbf{u}$ and ρ denote design and the topology variables, respectively, and G represents the profile induced by $\mathbf{u}$ and ρ.

In order to determine an unrolling that minimizes this objective function, methods from discrete optimization can be applied. To this end the profile geometry $G(\mathbf{u}_{opt}, \rho_{opt})$ is represented by a directed graph. A mixed integer programming model has been set up in order to determine a certain substructure within the graph, a so-called Steiner tree, which can then be interpreted as an unrolling. The manufacturing restrictions enter the optimization process in terms of graph theoretical constraints. To ensure their adherence research on the underlying mathematical structure has been carried out and combinatorial algorithms have been implemented [23]. The maximal number of single components the profile is made of can be given as an input parameter. Fig. 5 shows unrollings consisting of two and three components, respectively. Both of them are optimal with respect to the approximation of the profile geometry when imposing an upper bound of two respectively three as the maximal number of components (Fig. 5).

4.7. Optimal rail design

Fig. 6 shows a prototype of the optimized and regarding to manufacturability approximated cross-section of the multi-functional guide rail with the slide and the rolling elements.

5. Summary

By incorporating the positive aspects coming from the manufacturing, e.g. forming process into the product development process additional functionality of components can be generated and product complexity can be reduced. This is reached by choosing an appropriate manufacturing technology after having clarified the development task. Hereby the manufacturing-induced properties can systematically be integrated into the design process in order to generate additional functional benefit. Furthermore due to the comprising of methods of discrete and nonlinear optimization iterations are avoided and the process of detailing is no longer driven by experience based knowledge. It can be guaranteed, that the optimal solution under given restrictions is met. These methods enfold the whole process of embodiment design from regarding manufacturing-induced properties to considering restrictions caused by the production process in terms of optimizing steps of manufacturing the product. This approach generates an optimal result, that employs the potentials of a given manufacturing technology most suitably. Potential constrictions of product optimality on one hand go along with a significantly improved producibility due to the comprehensive integration of methods of optimization, which link restrictions of design and potentials of manufacturing at the best.

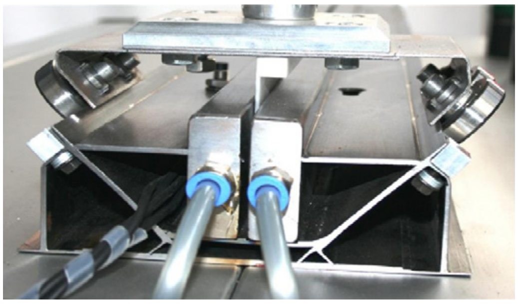

Fig. 6. Prototype of the linear guide.

Acknowledgements

The investigations presented in this paper were carried out within the research projects A1, A2, A3, B1, B4 and D1 of the Collaborative Research Centre 666 ‘Integral sheet metal design with higher order bifurcations—Development, Production, Evaluation’. The authors thank the German Research Foundation (DFG) for founding and supporting the CRC 666.

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