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SELECTIVE PRE-LOAD GENERATION: FINDING MANUFACTURING-INTEGRATED SOLUTIONS FOR LINEAR GUIDES

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Abstract

Pre-load is important for a linear guide's precision but can adversely affect its longevity. The idea of selectively adjusting pre-load for specified track sections of a linear guide is starting point for an innovative product design. Key challenge of realising linear guides with a selective pre-load generation is to integrate this additional function with low manufacturing effort. A continuous flow production with linear flow splitting has a high potential for realising a function integrated product design at low costs. Based on linear flow split linear guides, these potentials are extended towards manufacturing-integrated solutions (MIS) for linear guides with integrated selective pre-load generation. The design pattern matrix (DPM) aids the designer in systematically developing MIS based on generally applicable function carriers. Several MIS for linear flow split linear guides with a selective pre-load generation have been developed and two prototypes produced. The solutions are characterised by a comprehensive utilisation of the continuous flow production's design possibilities, resulting in products with high functionality and low manufacturing and assembly effort.

Keywords: Design for X (DfX), Design methods, Design Pattern Matrix (DPM), Manufacturing-Integrated Solutions (MIS), Technology

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1 INTRODUCTION - LINEAR FLOW SPLIT LINEAR GUIDES

The realisation of linear guides - used in various applications, like for example facade cleaning systems (Figure 1) - often requires subsequent manufacturing steps to provide the necessary surface quality of their rolling contact areas. This additional manufacturing effort can be justified when using the chosen manufacturing technologies to additionally increase the functionality of the product. Comprehensively exploiting the specific design possibilities of manufacturing technologies with respect to function integration is an approach to reduce manufacturing effort and increase functionality of the product at the same time. The cold forming technology linear flow splitting is predestined for applying this approach. Linear flow splitting offers a huge potential for developing manufacturing-integrated solutions for linear guides, characterised by a cost-efficient realisation and a high functionality in integral construction (Figure 1) (Wagner *et al*., 2017; Lommatzsch *et al.*, 2011a; Lommatzsch *et al.*, 2011b).

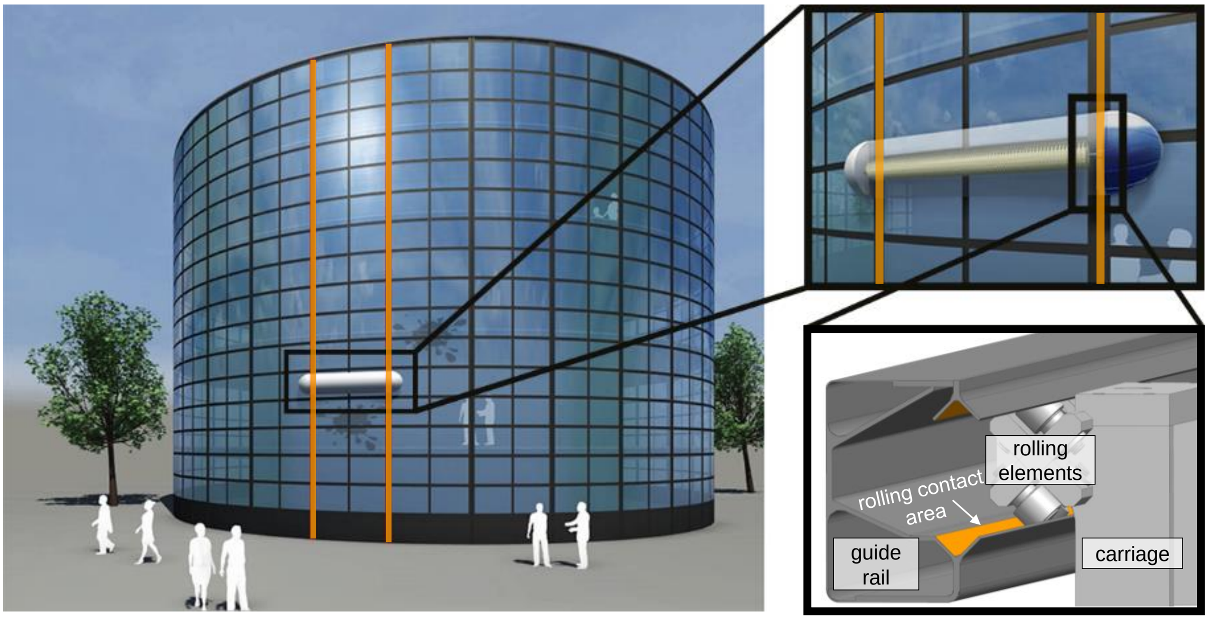

Figure 1. Facade cleaning system with an exemplary linear flow split linear system

The realisation of manufacturing-integrated solutions, like linear flow split linear guides, is only possible if the technology's specific possibilities are comprehensively exploited for design. Many DfM approaches provide design guidelines that emphasise technology-specific limitations in order to ensure a general manufacturability of the solution. (Tekkaya *et al.*, 2015) A new approach for developing manufacturing-integrated solutions concentrates on technology-specific design possibilities for realising product functions systematically enlarging the space of possible solutions. The technology-specific possibilities can be identified by analysing manufacturing-induced design elements and properties. Linear flow split flanges, for example, are manufacturing-induced design elements, characteristic for linear flow splitting, just like the web between the two flanges. The flanges' surface offers high hardness and reduced rolling contact fatigue. Due to these manufacturing-induced properties, the linear flow split flanges are especially suitable for the realisation of rolling contact areas for linear guides in integral construction (Figure 1) (Lommatzsch *et al.*, 2011a).

Combined with further technologies within a continuous flow production, like linear bend splitting, roll forming, high speed cutting (HSC) and laser welding, complex sheet metal profile geometries in integral construction can be cost-efficiently produced. Utilising the manufacturing-induced design elements provided by the whole continuous flow production for design allows the integration of additional functions into the sheet metal structure (Wagner *et al.*, 2014). Additional functions that support the precisely guided translatory motion within linear guides are especially promising, like, for example, a pre-load generation function. Pre-load is important to maintain a defined contact between rolling elements and rolling contact areas especially on linear guide rail segments with high manufacturing tolerances. While pre-load is necessary to provide a guided motion without backlash, an oversized pre-load leads to increased friction and decreased durability of the linear guide due to increased wear of the rolling elements (Ispaylar, 1997), exemplary shown for HIWIN® linear guides of the RG series (Figure 2).

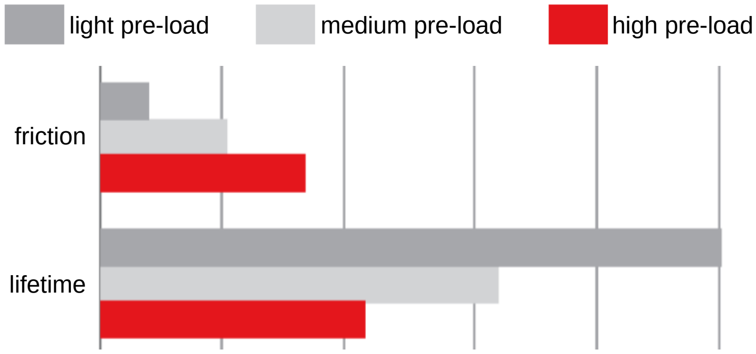

Figure 2. Friction and lifetime of HIWIN® linear guides depending on pre-load (HIWIN, 2016)

Considering the use of a linear guide, like the application within a facade cleaning system, increased precision is not necessary at all times. Maintenance runs of the linear motion system, for example, do not require particularly high pre-load and precision. Having a high pre-load only on specified track sections of the linear guide where higher precision is needed seems promising. The rolling elements experience less wear over the complete stroke distance while maintaining a guided motion without backlash where needed. Adding an auxiliary function to linear guides enabling the selective influence of pre-load offers high potential for product innovation - especially if the manufacturing-induced design elements provided by the continuous flow production are comprehensively utilised for realising the function. Illustrated by two prototypes that can selectively influence pre-load in linear guides, the paper introduces an approach based on the design pattern matrix (DPM) to develop manufacturing-integrated solutions starting from technology-independent, generally applicable, function carriers.

2 SELECTIVELY INFLUENCING PRE-LOAD IN LINEAR GUIDES

Adding the function "pre-load generation" to a linear guide requires the identification of generally suitable function carrier variants. Function carriers can be parts or principle solutions that realise one or more specific technical functions (Pahl *et al.*, 2007; Ehrlenspiel and Meerkamm, 2013; Wagner *et al.*, 2016). A variant-specific set of design-relevant properties characterises function carriers. Utilising the specific geometry and material properties of the linear flow split profile's web allows a direct integration of the function carriers into the continuously manufactured profile structure. The whole pre-load has to be directed through the web (Figure 3 and 4a).

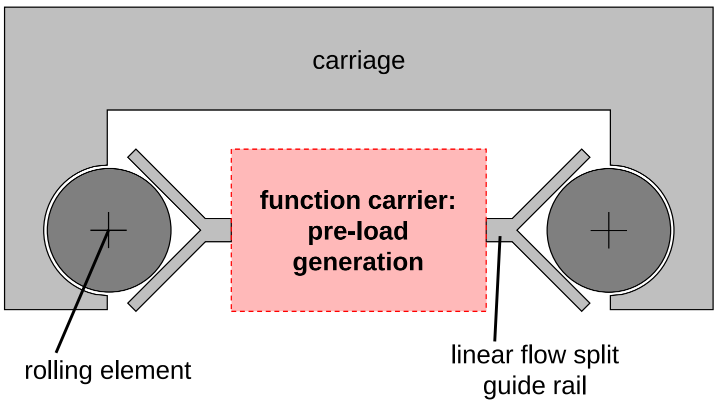

Figure 3. Design space of the function carrier for "pre-load generation" within a linear flow split linear guide

2.1 How to influence pre-load in linear guides

Linear guides, in general consisting of linear guide rail, carriage and rolling elements, can be considered as a tensed system (Figure 4a). Hence, the system's pre-load follows a linear force-displacement as given by Equation (1):

$$\Delta F_{pl} = c \cdot \Delta b \tag{1}$$

To increase the pre-load F_{pl} of the system, the stiffness of the system c or the pre-load distance Δb can be increased. Hence, there are two individual approaches to selectively influence the pre-load:

- Selectively changing stiffness
- Selectively changing pre-load distance

Figure 4b shows the joint diagram for a linear guide with increased stiffness leading to a higher pre-load while maintaining the initial pre-load distance. Figure 4c shows an increase of the interference between linear guide and carriage leading to an increased pre-load distance. The pre-load increases without having to alter the stiffness of the system. Tolerances along the linear guide rail can reduce the interference but do not lead to a loss of contact of the rolling elements as long as the pre-load remains greater than zero.

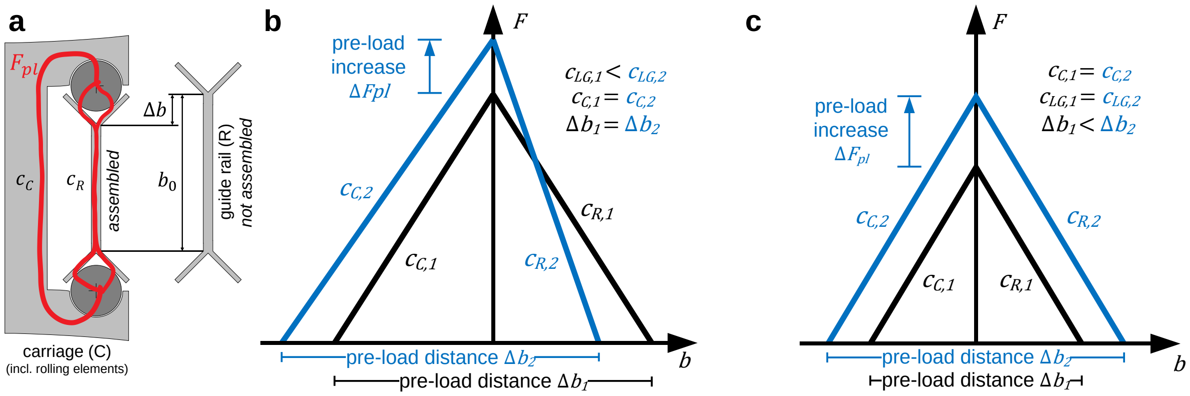

Figure 4. a: Tensed linear guide, b: Joint diagram for changed stiffness of the linear guide, c: Joint diagram for changed pre-load distance

2.2 Identifying function carriers for selectively influencing pre-load

Both approaches to influence pre-load require the identification and concretization of suitable function carrier variants that can be beneficially utilised to realise the pre-load generation function. The identification of corresponding design-relevant properties is crucial during this step.

2.2.1 Function carriers for changing stiffness

According to the equation for axial stiffness; Equation (2), the following material and geometric properties influence the stiffness of the linear guide:

$$c = \frac{E \cdot A}{b_0} \tag{2}$$

$$A = d \cdot l \tag{3}$$

The Young's modulus E and the cross section A of the guide rail directly influence the stiffness. The initial width of the guide rail b_0 is constrained by design space limitations. The thickness of the guide rail d and its length l influence the stiffness by determining the cross section A. Influencing the geometric properties d and l seems to be the most promising approach to realise the "pre-load generation" function to selectively change the linear guide's stiffness c. Figure 5 shows the resulting function carrier variants for the "selectively changing stiffness" approach. The function carriers differ in their thickness d but the stiffness could also be influenced by adjusting the length l of the corresponding section of the guide rail for each of the shown variants.

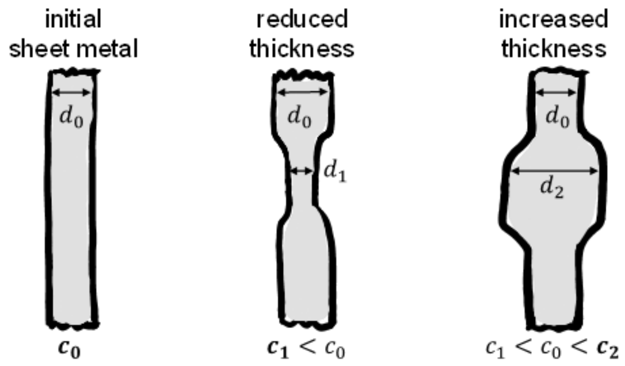

Figure 5. Function carrier variants for changing guide rail stiffness

2.2.2 Function carriers for changing pre-load distance

The second approach to influence the pre-load - by selectively changing pre-load distance - offers a larger range of possible function carrier variants. The underlying design-relevant properties are more extensive and cannot be described by simple equations like above. Properties, consisting of attribute and value (Birkhofer and Wäldele, 2008) structure the variants. The relevant properties are derived from appropriate physical effects and working principles. Variation of values for each identified attribute determines the number of possible variants:

- Physical effect: mechanic, hydraulic
- Working motion: translatory, rotatory
- Number of working elements: 1, >1

Combining different values of the three varied attributes leads to the desired function carrier variants. The entirety of possible combinations can be documented in the form of a variant tree (Figure 6), showing already promising function carriers for influencing the pre-load by changing the pre-load distance. There are even more attributes which could be considered. As a first step, the number of attributes is limited avoiding an oversized number of variants that can hardly be handled.

To now fully tap the continuous flow production with linear flow splitting's potential for function integration and manufacturing process integration, the technology's manufacturing-specific design possibilities have to be systematically exploited for the realisation of the identified function carrier variants for both approaches.

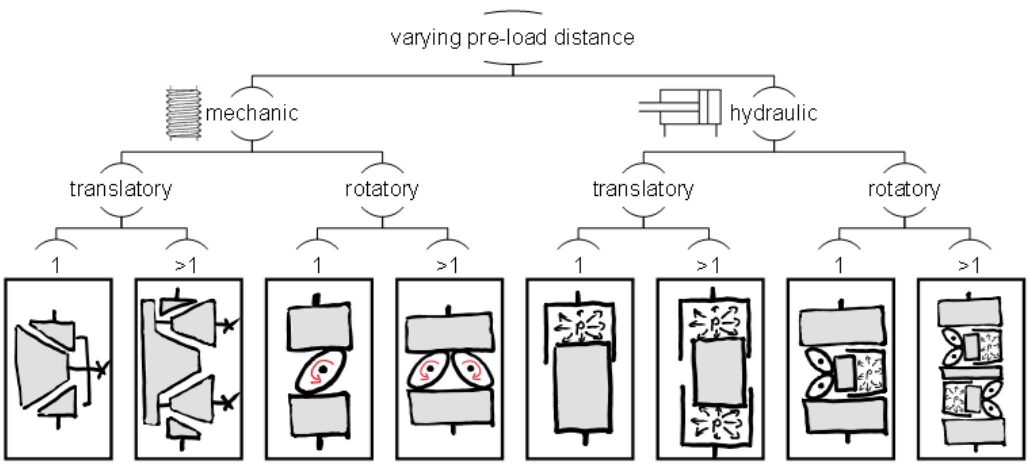

Figure 6. Function carrier variants for changing pre-load distance

3 LINEAR FLOW SPLIT LINEAR GUIDES WITH SELECTIVE PRE-LOAD

In subsequent concretisation steps, the designer continues to determine more and more properties of the function carrier to find the solution for selective "pre-load generation". Starting from the design-relevant properties of the identified function carrier variants manufacturing-induced design elements and properties of the continuous flow production have to be systematically utilised to realise the design-relevant properties. The processing of function carrier variants and manufacturing-induced design elements results in manufacturing-integrated solutions for the whole linear guide rail that can be cost-efficiently produced within a continuous flow production providing the required functions "guiding" and "pre-load generation".

3.1 Manufacturing-integrated solutions using the Design Pattern Matrix

The DPM utilises manufacturing-induced design elements for aiding the designer in systematically developing manufacturing-integrated solutions (Roos *et al.*, 2017). Manufacturing-integrated solutions can be systematically generated by linking manufacturing-induced design elements (column headings of the DPM) to the already identified function carrier variants (row headings of the DPM) (Figure 7). Feasible links between both elements are represented by design patterns (Wagner *et al.*, 2016), stored in white cells in Figure 7. Within a design pattern, a manufacturing-integrated solution for a design problem, a design choice recommendation and appropriate consequences are documented based on a property-based description (not illustrated in Figure 7) (Wagner *et al.*, 2016). Hatched areas indicate that no design patterns can be found or are known for that specific match of function carrier variant and manufacturing-induced design element. The remaining solutions make extensive use of the manufacturing-induced design elements of the continuous flow production. In terms of function integration, function carriers can be realised in integral construction without needing manufacturing-induced design elements of additional manufacturing technologies.

Figure 7 illustrates the way of generating manufacturing-integrated solutions starting from manufacturing-induced design elements of the continuous flow production and function carriers for the functions "guiding" and "pre-load generation". The depicted manufacturing-induced design elements of linear flow splitting, linear bend splitting, roll forming, HSC and laser welding are highly compatible to each other, allowing an easy combination of each provided design-element.

The generated design patterns can be easily combined cell by cell into manufacturing-integrated solutions (MIS1 to MIS3.2). MIS1 uses the linear flow split flange to realise the linear guide's rolling contact area. MIS2.1 to MIS 2.8 are solutions for generating pre-load by changing pre-load distance whereas MIS3.1 and MIS3.2 are solutions that can selectively change the stiffness of the guide rail. During the combination of different design patterns to one MIS, generally applicable rules and guidelines, like principles of embodiment design (Pahl *et al.*, 2007), still apply.

The result of applying the DPM are MIS that beneficially integrate the functions "guiding" and "pre-load generation" into the linear flow split guide rail. By implementing these solutions into specific guide rail segments the linear guide's pre-load can be selectively influenced within these segments.

3.2 Concretisation of manufacturing-integrated solutions

So far, the developed MIS contain only conceptual information about how to utilise a manufacturing technology for the realisation of the intended function carriers. Consequently, these solutions must be further concretised to design a specific embodiment. For this paper, two prototypes for the most promising MIS have been created.

MIS3.1 and 3.2 have both been concretised in the form of a prototype that allows the selective change of stiffness of the guide rail (Figure 8a and 8b). The prototype represents only the web of a linear flow split linear guide that is segmented into parts with varying stiffness. At the edge of the web, linear flow split flanges could be used to realise the linear guide's guiding function. Thickening or cutting the web out at specified points leads to a stiffness between 110 kN/mm and 540 kN/mm (Figure 8c and 8d). The resulting pre-load in the reinforced segment is up to 400% higher than in the cut out segment. HSC enables the simple realisation of the solution.

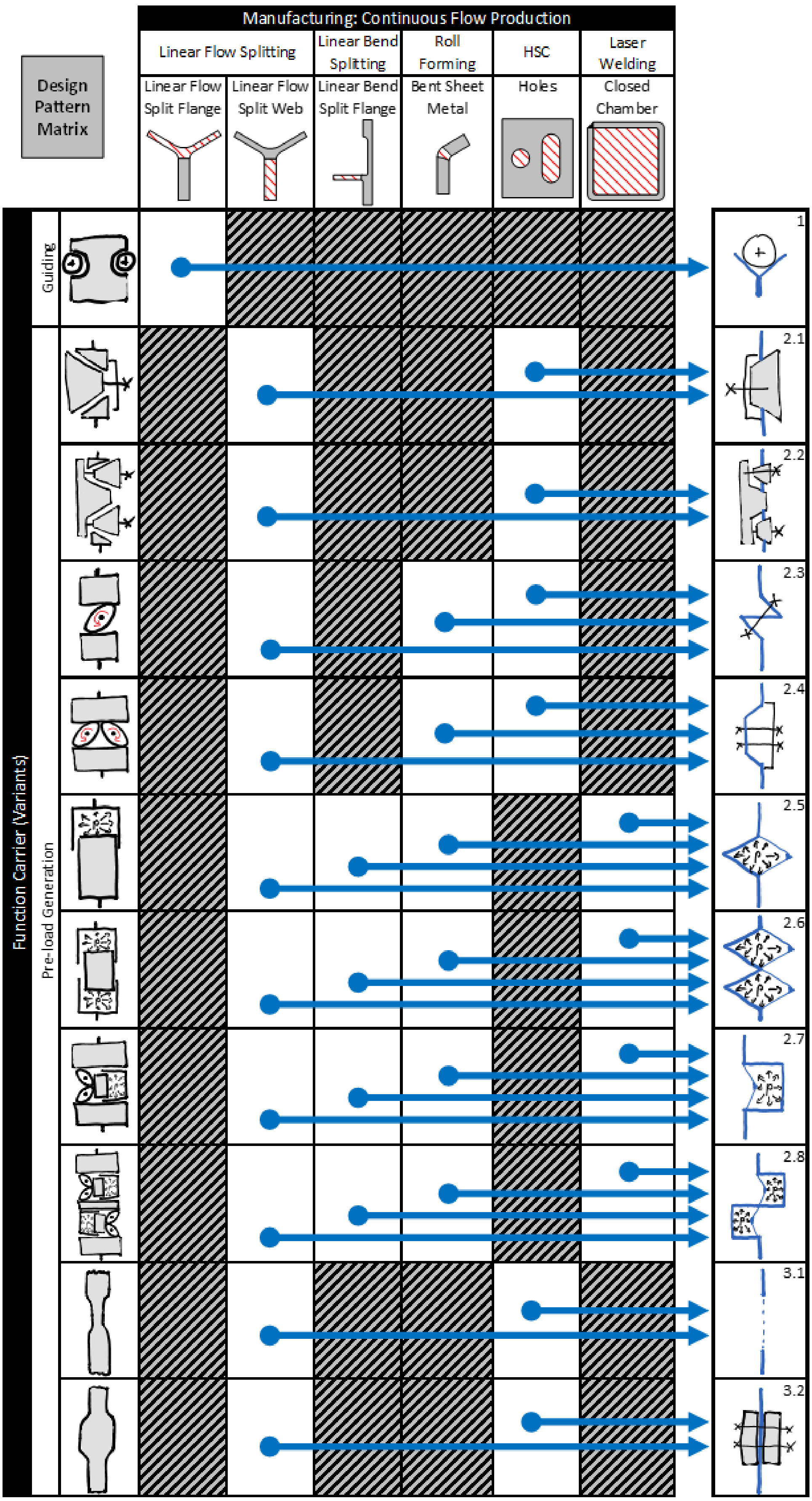

Figure 7. Design pattern matrix (DPM)

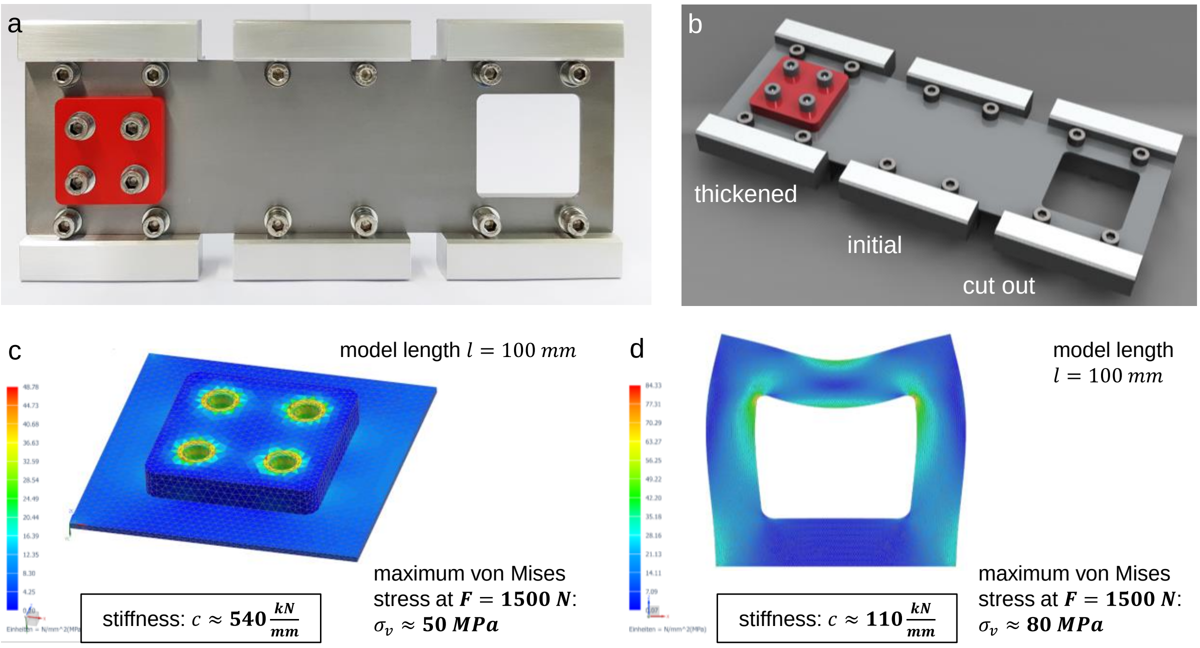

Figure 8. Solution for selectively changing stiffness of the guide rail (a: prototype, b: CAD model, c: FE simulation of von Mises stresses in thickened zone, d: FE simulation of von Mises stresses in cut out zone)

The concretised prototype of MIS2.3 in combination with MIS1 represents the solution that aims at a selective change of the pre-load distance. The compatibility of the required manufacturing technologies (linear flow splitting, roll forming, HSC) within the continuous flow production allows a cost-efficient manufacturing process (Figure 9a) (Wagner *et al.*, 2017). Ideally, applying pre-load with the help of MIS2.3 does not lead to an angular offset between the rolling contact areas (Figure 9b). In addition, small angular changes from φ_1 to φ_2 lead to only a small lateral offset Δy. Screws are applied for changing the intended pre-load. Due to self-locking, the screws do not need additional locking washers. Figure 10a and 10b show the prototypical realisation of the MIS2.3. By fastening the screws pre-loads up to 300 N can be applied per 30 mm profile length limited by the strength of the linear guide's material (ZStE340).

The two concretised and prototypically realised manufacturing-integrated solutions illustrate how a systematic and early consideration of manufacturing technological possibilities can lead to an easily manufactured design with high functionality within a single part. Being able to selectively increase the pre-load within linear flow split linear guides the solutions allow a targeted reduction of backlash.

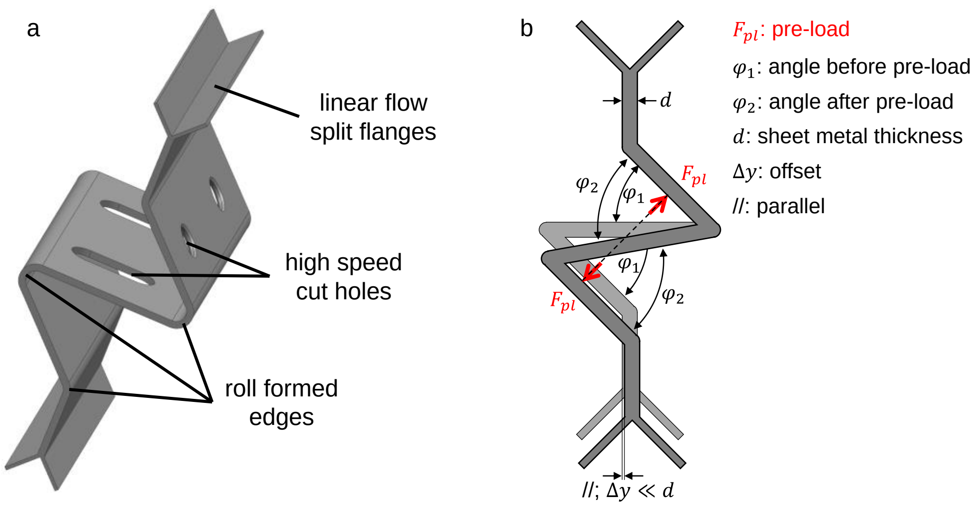

Figure 9. Manufacturing-integrated solution for selectively changing pre-load distance (a: displacement resulting from pre-load, b: concretised CAD model of the guide rail)

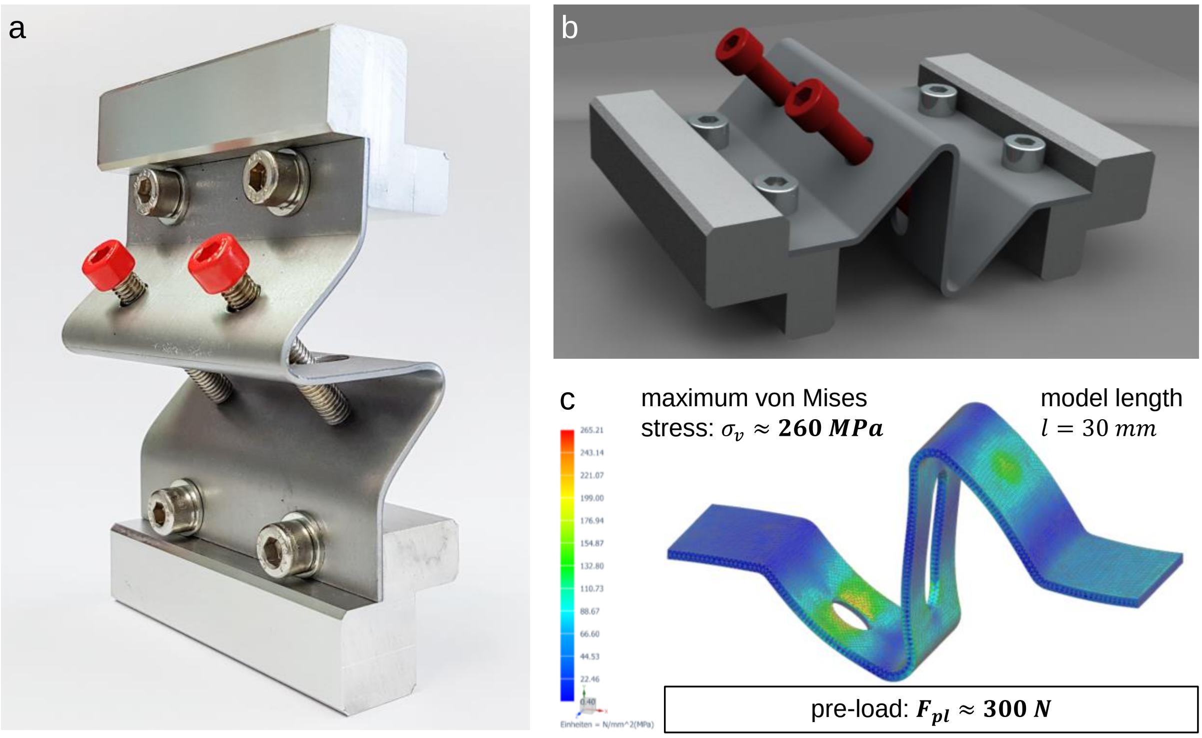

Figure 10. Solution for selectively changing pre-load distance (a: prototype, b: CAD model, c: FE simulation of von Mises stresses)

4 CONCLUSION

There are basically two ways to influence the pre-load of a linear guide: changing the pre-load distance or the stiffness of the tensed system. Using established design methods like systematic variation and combination of product properties, suitable function carrier variants for both approaches are identified. Manufacturing-integrated solutions for the identified function carrier variants are generated with the help of the DPM. Based on a uniform description by product properties, a defined link to existing design methods is established, allowing an easy implementation of the DPM into the development process.
The prototypically realised solutions exploit technology-specific design possibilities of the continuous flow production in terms of a cost-efficient realisation of the linear guide in combination with additionally integrated product functions. Especially integrating the pre-load generation function broadens the possible range of applications of linear flow split linear guides. The integral construction of the prototypes results in a low number of parts and necessary assembly processes. The continuous geometry allows a cost-efficient flow production. Once set up, production costs of a continuous flow production mainly depend on the material costs of the intended profile. In contrast, manufacturing large quantities of linear guides with the help of discontinuous manufacturing technologies would require significantly more manufacturing and assembly operations, leading to increased production costs.
Using process integrated joining methods like joining by linear flow splitting (Wagner *et al.*, 2015), additional actuator components could be added to the screws of the shown prototypes allowing a dynamic influence of the pre-load for different applications. The implementation of other established design tools into the procedure is generally possible. An enhanced morphological matrix could be used to combine solutions for different subfunctions into complex manufacturing-integrated product solutions. Further research will focus on finding ways to implement the DPM in earlier development phases. Its basic form as a manufacturing-integrated property matrix (Roos *et al.*, 2017) could be used during early phases to quickly identify the most promising function carriers in terms of manufacturing-integrated solutions. Hereby, the introduced procedure could be strategically utilised during design to reduce the necessary development effort as much as possible. In future research, the approach will be further extended beyond the early design phases, supporting the development of technology-pushed product ideas as a starting point for the realisation of novel manufacturing-integrated solutions.

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