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A CLASSIFICATION SYSTEM FOR SECONDARY DESIGN FEATURES FOR THE USE WITHIN SHEET-BULK METAL FORMING

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ABSTRACT

Estimating the potential of new emerging manufacturing technologies for the area of engineering design is crucial for the establishment of these processes in the industry sector. An example for such a new technology is sheet-bulk metal forming (SBMF): New parts can be designed due to the higher design freedom for design engineers and the possibility to integrate more functions by using more functional elements per part. Furthermore it is of high interest if this emerging technology can be used to substitute established manufacturing processes and produce parts with a higher functional density with less process steps and more robust processes. In this paper a new classification system is presented that enables the design engineer to classify parts with primary and especially secondary design features. On the one hand the classification system can be used to identify parts for which the established manufacturing process may be substituted by SBMF. On the other hand potential for new innovative solutions can be revealed.

Keywords: design for X, information management, new product development, feature classification, sheet-bulk metal forming

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1 INTRODUCTION

Saving resources is a crucial objective in the 21st century and is motivating intensive work in various research fields such as renewable energy, hybrid (or fully electric) vehicles or smart electrical grid. Lightweight design is another example that is particularly important for the automotive sector and can be achieved by different approaches: Decreasing the volume of specific parts (key components) or increasing the functional density per part are only two possibilities (Mallick, 2010). However, these lightweight approaches place new demands on key components which have to operate at their limiting capability due to increased loads and/or stresses. For example, the synchronizer rings in vehicle transmission units which feature precisely arranged gear teeth are in general made of brass. But to cope with higher loads they should in future be made of steel to benefit from higher strength and improved wear resistance (Song, 2008). In many cases current production processes are only able to deliver these new high performance components by means of many different sub-process steps and thus at high costs (Merklein, 2012). This motivates the research for new forming processes to produce high quality sheet metal components with heavily loaded functional elements. One possibility is to apply bulk forming operations to sheet metals which has led to a new class of forming processes with the overall designation sheet-bulk metal forming (SBMF) (Merklein, 2012).

In order to establish this new technology the potential of SBMF has to be revealed. Most of this potential resides in the substitution of existing manufacturing processes by SBMF and thereby decreasing the actual use of resources. However, in the sense of integrated product development (e. g. according to Andreasen, 1987) this requires an information exchange between the areas of engineering design and process engineering during an early phase of process development. But in fact important information for the process engineer in which direction the process is to be improved in a way that is reasonable both for the design engineer (e. g. for parts with new functional elements) and the process engineer (e. g. adding new parts to the scope of SBMF) is missing. Furthermore, a structured overview about parts with small but complex and functional secondary design feature (SDF) that are attached to a primary design feature (PDF) and that are can be produced by SBMF in principle, is not available.

The presented work is part of a research sub-project that is focusing on issues regarding the design for SBMF of parts with secondary design features (www.tr-73.de). The basic core-activities *synthesis* and *analysis* of design engineering (in accordance to Weber, 2009) will be assisted with a self-learning and thus knowledge-based engineering assistance system. This paper reports about the development of a classification system for SDF that is to be used within the development of SBMF-parts. At the beginning a closer view on SBMF is taken and the term secondary design feature is explained, along with several examples (Chapter 2). Furthermore, the need for a classification system for SDF which takes the specific requirements from SBMF into account is shown (Chapter 3). After presenting the classification system (Chapter 4) its application is shown by means of a use case (Chapter 5). With the classification system the potential of sheet-bulk metal forming regarding the substitution of existing manufacturing technologies is estimated qualitatively (Chapter 5).

2 SHEET-BULK METAL FORMING IN ACADEMIC RESEARCH

The class of SBMF processes consists of several well-known processes that are newly combined as well as extended in their application. SBMF processes are forming processes in which conventional sheet and bulk forming operations are combined. These processes are applied to sheets or plates. The processes summarized in this new class are characterized by the complex interaction between forming zones of high and low strains as well as locally varying 2- and 3- dimensional stress and strain states. Further characteristic aspects of the considered processes are incremental cyclic loading of the material and the influence of the materials anisotropy on the resulting forming (Merklein, 2012).

SBMF and the related fundamentals are being developed within the *Transregional Collaborative Research Center* (SFB/TR73) in Germany. Different subprojects research on different issues e. g. material flow, tool development, coatings, material models or adaptive finite element methods. This contribution is part of a subproject that deals with the issue of “Design for sheet-bulk metal forming”. Its objective is the development of a self-learning engineering assistance system that supports the design engineer during the development of sheet-bulk metal formed parts. Its knowledge-based analysis component is suitable to analyze a part design regarding manufacturability in an early product development phase (Breitsprecher, 2012).

2.1 Sheet-bulk metal formed samples

Sample parts that are typical for SBMF and corresponding SDF are shown in Figure 1. These samples are results from different subprojects of the SFB/TR73 where test productions were performed. The samples cannot be used for a specific industrial application but with respect to the characteristics (diameter, sheet thickness, material) they follow the principle of real parts, for example synchronizer rings, gear drums, disk gears or control levers.

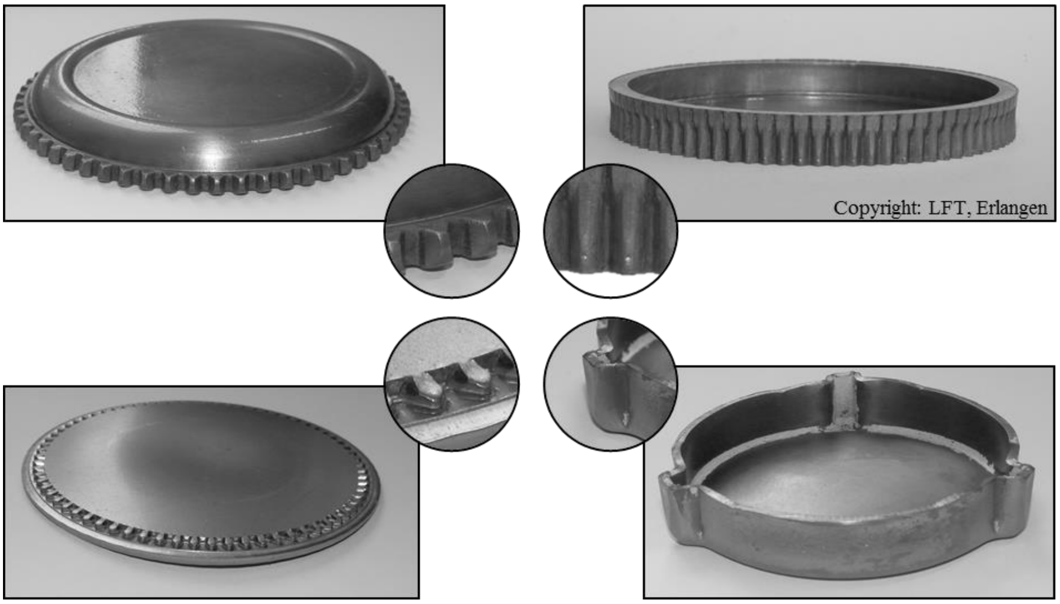

Figure 1. Samples of typical SBMF parts from test productions with different SDF. The diameter is about 80mm, the sheet thickness is 2mm and the material DC04 (1.0338).

2.2 Design features within sheet-bulk metal forming

The distinction of primary design features and secondary design features of SBMF parts within this contribution is oriented towards the feature of a component with the effective area where a specific function is fulfilled (Pahl, 2007). Taking the synchronizer ring (Figure 2) as an example two functions can be highlighted (Birch, 2012).

Figure 2. A synchronizer ring (produced by sintering) with exemplary SDF.

At first a friction momentum is necessary for synchronizing the pinion shaft and the speed gear and secondly preventing the sliding sleeve from shifting before the synchronization is finished. The effective area for the first function is a friction cone on the inner side of the synchronizer ring. The second function is fulfilled by the locking teeth which are equally distributed along the outer diameter. Hence, in the present context a SDF is a geometric feature where the effective area of the function fulfillment is situated. This understanding aligns with the common idea of features in literature (VDI 2003, Nasr 2006). Furthermore, it is rather small compared to the overall size of the component. As mentioned the SDF can be set into geometric relation to the main shape of the component (inside/outside of the ring) which is called the primary design feature (PDF). Thereby, the function of a PDF in this contribution is mainly to “carry” the SDF.

3 CLASSIFICATION OF DESIGN FEATURES IN LITERATURE

The meaning of the designation *feature* depends on the contexts and on the specific domain. For example, in engineering design it refers to a geometry area with notches or grooves etc., while in manufacturing it refers to slots, holes and pockets (Devireddy & Ghosh, 1999). The following itemization covers only a few further definitions of a feature:

- “A region of interest on the surface of a part.” (Pratt & Wilson, 1985)
- “An entity used in reasoning about the design, engineering, or manufacturing of a product.” (Sreevalsan & Shah, 1992).
- “A technical information item which represents one or more products in the (technical) region of interest. A feature is described by an aggregation of characteristics of a product.” (VDI 2218)

Despite this many definitions, the basic idea is that features represent the engineering meaning of a part’s geometry, of an assembly or a production process step (Nasr, 2006). However, classification of features is totally application dependent. It is very difficult to make an application-independent classification of features, whether they are of primary or secondary level.

The research domain of design feature classification can be traced back to the 1960’s when Optiz (1960) introduced his classification system for workpieces. His objective was the assistance of the search for frequently used components. Basis of his classification system is the definition of SDF with one specific function. Examples are grooves for O-rings or mounting elements (e. g. tapped hole). These features correspond to nowadays high grade semantic features as they are described for example by Wartzack (2000). Zimmermann (1967) suggests the additional distinction of SDF from 1st to 3rd order. Form features which can be added to the part independently from the shape of the main design feature are SDF of a higher order. To ensure the clarity of form catalogues features of higher order are not to be depicted. Thus, Zimmermann strives for the distinction of main manufacturing process steps from finishing process steps.

With the increasing computing power in the 1980’s the establishment of computer aided methods began. Several approaches for automatic feature classification and recognition were proposed. Anderson, Henderson and Staley (1983) developed an approach with a grammar-based (syntactic) pattern recognition that could classify holes based on how they are manufactured. A further approach from this decade was presented by Joshi and Chang (1988). Within their graph-based approach, the boundary representation of a part is translated into a graph, whose nodes represent the faces of a part and the arcs represent the part edges. A graph also includes information about the convexity or concavity of the part edges. The graph is then decomposed to its sub-graphs by removing all of its nodes which are surrounded by convex edges. The resulting sub-graphs are analyzed to determine their feature types with the aid of feature template graphs.

The graph-based approaches were further developed by Zhao, Gosh and Link (1990) who used a wireframe model to develop an algorithm for recognizing machined features. Their approach was quite suitable for symmetrical parts but did not use three dimensional solid modeling or any standard format for representing a workpiece digitally. A next step was the approach of Venkata-raman, Sohoni, and Kulkarni (2001). They also developed a graph-based feature recognition system for user defined features (UDF). A UDF is represented by a sub-graph and integrated in a top-level graph of the part. The feature recognition algorithm then searches for similar sub-graphs. Within this approach a wide range of features like pockets with several side faces can be detected.

Recent developments like the approach of Abouel-Nasr and Kamrani (2006) proposed an intelligent feature recognition methodology for three-dimensional prismatic parts modeled by constructive solid geometry (CSG) techniques. In order to classify features the boundary representation of a part (B-rep) is used to derive further geometrical information of the part. Afterwards a geometric reasoning algorithm is used to recognize different features of a part like steps, holes or chamfers. Sunil and Pande (2008) developed a features classification and recognition system for freeform surface models. Based on the part’s STL file format the properties of facets such as edges and vertices such as gauss or mean curvature at vertices, orientations of a facet normal, shape structures of triangles, dihedral edge angles (angle between facets) are computed to identify and classify different features.

3.1 Assessment of existing classifying systems

Basically the existing classification systems classify PDF and sometimes dominant SDFs. SDF that are small in proportion, do appear occasionally or seem to be inconspicuous are rarely taken into account. Zimmermann (1967) offers a quite universal structure according to the position, shape or number of SDF. However, these different SDF have too much influence on the main manufacturing technology which is to be used. An insufficient overview of the available form features may cause a wrong or time- and money consuming decision.

Most classification systems were developed within the scope of a specific manufacturing technology. This offers the advantage of a structured and clear classification, but on the other hand the application for new or other manufacturing processes is not possible.

The classification according to position, manufacturing or function of a SDF is always combined with a detailed numbering system. This leads to a high level of abstraction of geometric shapes, dimensions or other information. An immediate interpretation of the depicted facts without comprehensive knowledge of the classification system is not possible. New users of the system need a detailed documentation in order to decrypt the numbering system. The classification systems that are listed above have in common that the classification of a new part or SDF is based on the subjective judgment of a single user. This judgment depends (unconsciously) on the knowledge and experience of the user. Hence, a continuous quality and usability of the classification system cannot be taken for granted.

The computer aided approaches that emerged during the last decades brought remarkable advances in terms of automatic feature classification or recognition, respectively. However, each contribution shows some weaknesses regarding different aspects. The work of Anderson, Henderson and Staley (1983) shows limitations that are specific for classification systems based on syntactic patterns. Due to the limited grammar the method has difficulty in parsing objects and furthermore structural information, necessary for the classification, is lost due to interactions among feature types. The graph-based approach of Joshi and Chang (1988) for classifying a feature is based on several heuristics. Those heuristics were quite extensive and covered a high number of different features. However, the approach fails to help the recognition of interacting features. Even more heuristics to handle some types of feature interactions were implemented, but the possible interactions that may be found in complex parts are almost unlimited. Hence, it is not possible to enumerate all interactions with heuristics. The way a graph is decomposed has a severe impact on the efficiency and the capability of recognizing interacting features. Furthermore, their approach clearly focuses on workpieces machined with several process steps and not equipped with secondary design features. The method of Zhao, Gosh and Link (1990) is sufficient for machined axis-symmetrical workpieces like canonical parts. Furthermore, this methodology did not use three dimensional modeling techniques for solids or any kind of standard format and is thereby very limited regarding the applicability on new cases. Venkataraman, Sohoni, and Kulkarni (2001) improved graph-based approaches but are also hindered by the major problem, namely the lack of recognizing intersecting design features. Since SBMF focuses on functional integrated parts where the chance of intersected SDF is very high, this approach is not appropriate for our purpose. The methodology proposed by Abouel-Nasr and Kamrani (2006) is restricted to those solid primitives (e. g. prisms, cylinders, bowls or kinds of a polyhedron) that are useful for features-based design by CSG techniques. However, the complex secondary design features as they are depicted in Figure 1 cannot be represented or designed with CSG techniques. Hence, the proposed approach is not applicable for our purposes. Finally, the approach of Sunil and Pande (2008) focuses on sheet-metal parts with freeform surfaces and uses STL-files to classify either face-based, edge-based or transitive (between faces) features. These features only cover classical shapes like holes, louvers, notches or bends. A STL representation is a triangulation of the original shape and always involves a geometric deviation between the original and the triangulated surface. This deviation increases dramatically if an area of the part is small compared to the overall part, which is a one important characteristic of SDF in this contribution.

3.2 Requirements on an improved classification system

Core idea of the classification system presented in this paper is to assess a part (real or digital represented) with form features if it is potentially manufacturable with SBMF. The aspects clarity and uniqueness of design features are emphasized in order to ensure an easy use for later application, e. g. within a CAx environment. For this reason the term *design feature* is used rather than form element.

Based on the developed classification system the potential of SBMF to expand actual process limitations shall be estimated. On the one hand this potential is given when SBMF can be used in principle to substitute mature manufacturing processes that are necessary to produce a specific part. On the other hand potential is given, when the developed classification contains classes for which no actual part or SDF can be found in existing products. This way the design engineer can offer new fields of application to the manufacturing engineer for his technology. Of course, a detailed process planning in this case is obligatory.
The user shall not be misled during the estimation of this potential. Hence, the terms to describe the different classes have to be independent from the part's function or its current manufacturing process. This leads to a classification system solely based on geometry.
The objective classification of design features by a user is an important property of such classification systems or tables. Even statements about the size of a design feature without naming a scale or geometric reference is problematic, because of the different sensations of different users. Absolute quantitative characteristics like the specific size of a design feature are to be avoided.
Accuracy and extent of a classification system shall always be according to the intended purpose (Greska and Franke, 1997). Existing classification systems are too extensive – the works of Zimmermann (1967) and Opitz (1966) are spread over several tables – and do not match with the characteristics, which are necessary to describe the SDF manufactured by SBMF. Hence, a clear and easy understandable classification that can be displayed in one table is necessary. Furthermore, an automatic classification system or algorithm, like the ones presented above, needs a suitable digital model of the workpiece. Since such a model is not granted - e. g. for reasons of know-how protection - a classification system that can be used for "analog" workpieces is preferred.

4 CREATION OF THE CLASSIFICATION SYSTEM

4.1 Design of the classes for PDF and SDF

In the following the characteristics for the description of a SDF are determined. On the one hand at least one common characteristic is necessary to form a design feature class. On the other hand classes have to be sufficiently delimited from each other. Based on the formulated requirements only geometric characteristics are taken into account.
The semantic features of a class are based on the system provided by Zimmermann (1967). He uses the groups *positive form*, *negative form* and *orifice* (or opening). The research work for this paper refines these semantic features to the design feature class DFC#1 elevation, DFC#2 deepening, DFC#3 toothing, DFC#4 orifice and DFC#5 corrugation/knurrling.
Elevation and deepening are basic forms. The direction of an elevation or a deepening will be cleared with an additional characteristic related to the PDF. Deepening is a feature like a groove or a hole (not through the whole solid). The introduction of the class toothing is problematic at first sight, because it can both be an elevation and a deepening. However, the very idea is that the manufacturing of a toothing with established processes means a high effort with additional process steps and tools. With SBMF it is possible to manufacture a toothing with a single forming process (Merklein, 2012). An orifice or an opening is a SDFs that penetrates the whole PDF. If it does not, it is to be assigned to the class deepening. Corrugations or knurling are structures on the part's surface. In contrary to a toothing there is no specific preferential direction.
After the determination of the design feature classes, each class is subdivided in up to three different sub-classes with specific characteristics. The choice of these characteristics does intend to ease the estimation of the potential of SBMF. The basic assumption is that the PDF has a symmetric shape (e. g. ring, tube, round plate). The additional sub-classes (characteristics) are the side of the PDF where the SDF is attached, the base area where it is attached and the size of the cross-section of the SDF.
Within the class *side* it is distinguished, whether the SDF is attached on the inner side or on the outer side of the PDF, assumed that this is clear to state e. g. for a ring, a tube or a cup. It can of course not be stated for plates. The vector of the *base area* can either be in axial direction of the PDF (speaking of an *abutting face side*) or in radial direction (speaking of an *arched surface*). The sub-class cross-section is used to estimate the size of a SDF compared to the PDF or the blank used for the SBMF process. The cross-section of a SDF can either be similar to the sheet thickness or not (thinner and thicker). If it is a similar thickness than sheet metal forming will be used rather than bulk metal

forming and vice versa. In the case of DFC#4 a distinction regarding the side where the SDF is situated and the size of the SDF is not necessary.
As mentioned before the presented sub-classes depend on a more specific description of the PDF. In general, four different PDFs are determined viz. plate, ring, sleeve/tube and cup. The SDFs are necessary to fulfill the main function whereas the PDFs have mainly the function of carrying the SDF. Hence, the PDF are not divided into further sub-classes. The design features plate and cup may show a hole/drill. The specific characteristic for a ring can be the ratio between the outer and the inner diameter or he remaining area of a ring with material thickness similar to the sheet thickness. The next step is to find a suitable representation for this system of classes.

4.2 Conceiving of a suitable representation

As a representation two very basic but different methods may be applicable: a hierarchical tree structure or and classification matrix or table, respectively. Advantage of the tree structure is the similarity to a data input form where the user is asked stepwise for specific information. This would ease a computer-aided version of the classification system. In opposition the presentation is less compact and less clear compared to a matrix. Furthermore, a matrix offers the chance to identify not filled areas where new form features and thus new products are possible. Hence, a matrix is the most suitable representation. The classes and sub-classes described in 4.1 are shown in the matrix of Table 2 (page 7). The cells contain classified SDF from the example (A1-B3, Table 1) and the amount of classified SDF for these cells. At the point of completion of the paper more than two dozen SDF from nine different parts were classified. More parts are being analyzed, but can of course not be included in this overview.

5 APPLICATION OF THE CLASSIFICATION SYSTEM

5.1 Classification of SDF of existing parts

The classification system was used to analyze several parts from different products, such as an automatic dual clutch transmission and an automotive seat system (Figure 3). From these demonstrators several parts where analyzed regarding SDFs. Examples for these parts are a parking lock gear and a seat adjustment as shown in Figure 3. The whole analysis was performed manually.

Figure 3. Automatic dual clutch transmission (ZF Friedrichshafen AG, 2013) and seat adjustment mechanism (Brose Fahrzeugteile and Feintool, 2013)

Table 1 shows a selection of various parts from the automatic dual clutch transmission. Most parts have more than one SDF and are listed in Table 1 starting from (A). The lamellae carrier (B) is taken as an example of the straightforward classification task. Three different design features can be seen: holes or slots (B1), axial stages or stripes (B2) and an abutment or quadratic pin (B3). According to chapter 2.2 the highlighted features show every characteristic of a SDF. First of all they are all small compared to the overall size of the workpiece. Furthermore, each of them fulfills a specific function like flow control of lubricant (B1), centering/mounting of steel lamellae and torque transmission (B2) and positioning of the lamellae package (B3). Thus, the highlighted design features have been correctly identified as SDF. The PDF in this case is a tube/sleeve or a cup respectively. In the case of the SDF B3 the classification with the matrix (Table 2) is as follows: It can be seen as an *elevation* on the *arched face site* of the PDF, situated on the *outer side* with a cross section *smaller* than the sheet thickness. Thus, the term B3 can be found in the corresponding field of Table 2. At the point of completion of the paper more than two dozen SDF from nine different workpieces were classified.

Table 1. Selection of analyzed parts with SDF

A1	locking teeth (Fig. 1)
A2	friction cone (Fig. 1)
A3	abutment
A4	radial grooves
A5	axial grooves
B1	holes, slots
B2	axial stages/stripes
B3	abutment, quadratic pin

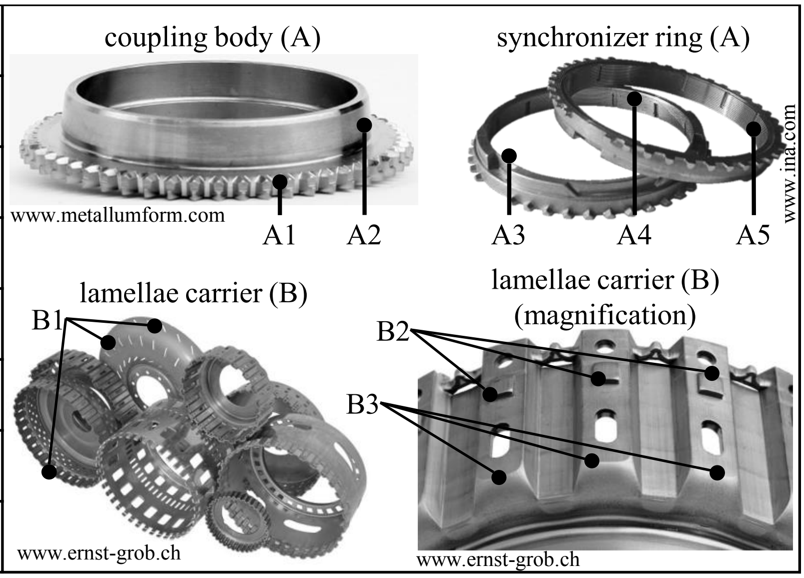

Table 2. Classification system matrix for the use within sheet-bulk metal forming.

	PDF side	inner side		outer side	
	SDF cross section / PDF base area face side	= sheet thickness	≠ sheet thickness	= sheet thickness	≠ sheet thickness
Design feature class #1 **elevation**	abutting face side		1 SDF		2 SDF
	arched face side			A3, B2, +1 SDF	A2, B3, +2 SDF
Design feature class #2 **deepening**	abutting face side				
	arched face side		1 SDF		1 SDF
Design feature class #3 **toothing**	abutting face side				
	arched face side	1 SDF	3 SDF	A1, +3 SDF	
Design feature class #4 **orifice**	abutting face side	B1			
	arched face side	B1			
Design feature class #5 **corrugation/ knurling**	abutting face side	1 SDF		1 SDF	
	arched face side	A4, A5		1 SDF	

5.2 Estimating the potential of sheet-bulk metal forming

For several parts the potential of SBMF to substitute the actual manufacturing processes can be shown. The teeth of the synchronizer ring in Figure 2 and Table 1 (A1) were manufactured during production experiments as Merklein (2012) shows (Figure 1, left upper corner). The combination with a deep-drawing process is possible and the cone-shaped friction surface (A2) manufacturable. With respect to

the lamella carrier the axial stages/stripes (B2) and the quadratic pins are similar to already manufactured SBMF parts or SDF respectively. The SDF B2 could be deep-drawn as shown in Merklein and Schneider (2011) (Figure 1, right lower corner). In Sieczkarek (2012) incremental forming is introduced as a SBMF process that can produce SDF like B3. Here the material has to flow perpendicular to the sheet thickness in a very small area which is a strength of incremental forming.
As mentioned before the potential of SBMF can also be revealed were empty cells in Table 3 can be seen. Especially for elevations some applications are conceivable, either on the inside or the outside of the abutting face side of a cup (see Figure 4, left). This example may be used for integrated roller bearing seats. Furthermore the matrix in Table 3 shows several examples for toothing on outer and inner arched face sides but no one for toothing on the abutting face side. Such a part can be equipped with an integrated Hirth-joint in order to transmit high torque within a very small design space (see Figure 4). For such a Hirth-joint SBMF offers a typical high precision and the strain hardening during the forming process increases the strength of the part (Merklein, 2012). This could be used for the clutch plate carrier which is currently connected with an additional weld seam.

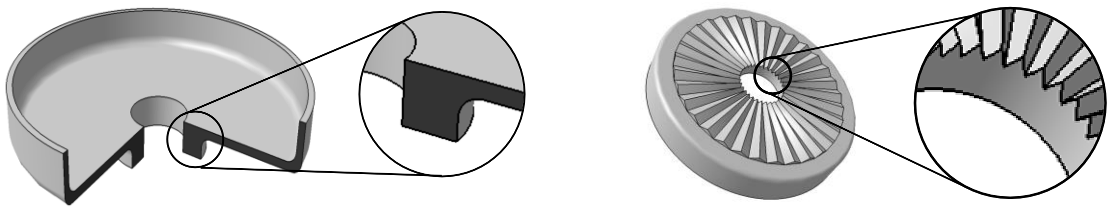

Figure 4. Potential SDF derived from not filled cells in Table 3 like parts with integrated bulk-formed bearings seats (left, cut-view) or a formed Hirth-joint (right)

6 CONCLUSION AND OUTLOOK

Objective of this paper was the development of a classification system for SDFs during the development of the new group of manufacturing processes SBMF. The work is part of a SFB/TR73 sub-project that is focusing on the design for SBMF of parts with SDF (www.tr-73.de). The developed classification system was used to classify several SDF from workpieces which are installed in different products. Afterwards the potential of SBMF was estimated. For several SDF SBMF can be used in principle to substitute current manufacturing processes. This estimation is based on previous production experiments within the SFB/TR73. For the empty cells of the classification matrix several design concepts were presented which can be manufactured by SBMF in principle and may offer new and interesting applications. The classification system also improves the information exchange between engineering design and process (manufacturing) engineering, because it serves as a basis for discussions. In accordance to the idea of integrated product development this is an advantage over existing automatic classification systems from the literature. A disadvantage of every classification system (and of the presented) is their narrowness. The stronger the intention for a clear and detailed listing of features characteristics, the smaller is the choice of possible terms. It is very difficult to make an application-independent classification of features, whether they are of primary or secondary level. Also detailed examinations (e. g. simulations) regarding the manufacturability of classified SDF via SBMF are necessary in any case. However, the classification system gives a first hint from the view of the design engineer and encourages communication between design engineers and process engineers. An important issue for future improvements on the classification is the consideration of different SDF that can be combined in one workpiece. Such combinations cannot be taken into account with the classification system at this point but are a core objective of the SFB/TR73.

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REFERENCES

Abouel Nasr, E. and Kamrani, A. (2006) A new methodology for extracting manufacturing features from CAD system. *Selected Papers from the 34th ICC&IE*, Vol. 51, No. 3, pp. 389-415.

Anderson, D., Henderson, M. and Staley, S. (1983) Using syntactic pattern recognition to extract feature information from a solid geometric database. *Computers in Mechanical Engineering*, Vol 2, No. 2, pp. 61–66.

Andreasen, M. and Hein, L. (1987) *Integrated Product Development*. Bedford: IFS Publications.

Birch, T. (2012) *Manual drivetrains and axles*. Boston: Prentice Hall.

Breitsprecher, T. and Wartzack, S. (2012) Architecture and realization of a selflearning engineering assistance system for the use within sheetbulk metal forming. *9th Norddesign*, Aarlborg (Denmark), 22.08.2012, Aarlborg: Aarlborg University, pp. 79-86.

Brose Fahrzeugteile GmbH & Co KG (2013) *Structures for front seats* [online] http://www.brose.de/shared/img/produkte/brose_16350_b_klein-frei1.jpg (03.01.2013)

Devireddy, C. and Ghosh, K. (1999) Feature-based modeling and neural networks-based CAPP for integrated manufacturing. *Int. Jour. Computer Integrated Manufacturing*, Vol. 12, No. 1, pp. 61–74.

Greska, W., Franke, V. and Geiger, M. (1997) Classification problems in manufacturing of sheet metal parts, *Computers in Industry*, No. 1, pp. 17–30.

Joshi, S. and Chang, T. (1988) Graph-based heuristics for recognition of machined features from 3D solid model. *Computer Aided Design*, Vol. 20, Nr. 2, pp. 58–66.

Mallick, P. (2010) Materials, design and manufacturing for lightweight vehicle. Boca Raton: CRC.

Merklein, M. and Schneider, T. (2011) Functional Integration of Sheet Metal Parts by Deep Drawing, *10th International Conference on Technology in Plasticity*, Aachen (Germany), 25.09.2011, Düsseldorf: Stahleisen, pp. 1036-1041.

Merklein, M., Allwood, J., et al (2012) Bulk forming of sheet metal, *CIRP Annals - Manufacturing Technology*, Vol. 61, No. 2, pp. 725–745.

Opitz, H. (1966) *Werkstückbeschreibendes Klassifizierungssystem*, Essen: Girardet.

Pahl, G., Beitz, W., Blessing, L., Feldhusen, J., Grote, K. and Wallace, K. (2007) *Engineering Design*, London: Springer.

Pratt, M. and Wilson, P. (1985). Requirements for support of form features in a solid modeling system. *Final Report in CAM-I Report*, R-85-ASPP.-01.

Sieczkarek, P., Kwiatkowski, L., Tekkaya, E., et al (2012) Improved Tool Surfaces for Incremental Bulk Forming Processes of Sheet Metals. *Key Engineering Materials*, Vol. 504, pp. 975-980.

Song, X. and Jie, Z. (2008) A Research on Steel Synchronizer Gear Ring's Precision Forging, *Materials Science Forum*, Vol. 575-578, pp. 226–230.

Sreevalsan P. and Shah J. (1992) Unification of form feature definition methods. *Proceedings of the IFIP WG 5.2 Working Conference on Intelligent Computer Aided Design*, Columbus (USA), 30.09.1991, Amsterdam: North-Holland, pp. 83–106.

Sunil, V. and Pande, S. (2008) Automatic recognition of features from freeform surface CAD models. *Computer Aided Design*, Vol. 40, No. 4, pp. 502-517.

Venkataraman, S., Sohoni, M. and Kulkarni, V. (2001) A graph-based framework for feature recognition. *Symposium on Solid Modeling and Applications*, Ann Arbor: MI, pp. 194-205.

Verein Deutscher Ingenieure (VDI) (2003) *2218 Information technology in product development*. Berlin: Beuth.

Wartzack, S. and Meerkamm, H. (2000) 'Continuous computer support in the product development process by the use of high grade semantic features', *Konstruktion*, No. 3, pp. 24–26.

Weber, C. (2005) CPM/PPD – An extended theoretical approach to modeling products and product development processes, *2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and* Processes, Berlin, 07.-08.07.2005, Stuttgart: Fraunhofer-IRB-Verlag, pp. 159-179.

ZF Friedrichshafen AG (2013) *Media services – Product images* [online], http://www.zf.com/corporate/en/press/media_service/images/product_images/product_images.jsp (03.01.2013)

Zhao, Z., Ghosh, S. and Link, D. (1990). Recognition of machined surfaces for manufacturing based on wireframe models. *Materials Processing Technology*, Vol. 24, No. 1, pp. 137–145.

Zimmermann, D. (1967) *ZAFO – Eine allgemeine Formenordnung für Werkstücke*, Stuttgart, Günter Grossmann.