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4.4 Measurement strategy for a production-related multi-scale inspection of formed work pieces

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Abstract
The technology of sheet-bulk metal forming provides numerous advantages in the field of manufacturing. Work pieces with filigree and complex structures can be formed by only a few forming steps. To ensure a sustainable and effective production, the forming process has to be controlled by a production-related measurement system. A measurement system, which meets the high requirements of a forming process like a short measuring time, a high measuring point density and the ability to measure different features at the same time, is a multi-scale fringe projection system with multiple sensors of different resolutions. However, an adapted definition of a measurement strategy is necessary in order to enable a rapid conformity decision of the manufactured work piece based on the evaluated measurement data and thus to be able to inspect as many work pieces as possible. It allows to correct the manufacturing during a primary forming process and to assure a sustainable forming process.
Keywords:
Fringe projection; multi-scale measurement; sheet-bulk metal forming

1 INTRODUCTION

In times of increasing raw material costs, saving resources provides not only economical and sustainable advantages but also monetary benefits. Especially by improving production technologies, the reduction of the consumption of raw materials is possible. The aim is on the one hand, to generate the product with as less material and energy as possible. On the other hand, the product itself should be as light but also stabile as possible. In many cases, these demands could only be partially met by the current production processes. Indeed, they are able to deliver lightweight structures and products, but only at high cost. Therefore, this state of the art motivated the search for a new high performance forming method. The development of the sheet-bulk metal forming enables the production of high quality sheet metal components with highly loaded functional elements [1].

With the sheet-bulk metal forming technology the production of complex work pieces in only a few forming steps is possible with a minimum of required material. The increasing number of integrated function elements and the reduction of required material and process steps, which is attended by the reduction of energy consumption, is possible by an three dimensional material flow. Due to this new method filigree structures as well as geometric unequal features can be produced in only one step [1]. In order to research the new technology and their possibilities, the transregional collaborative research center (Transregio) 73 as a joint research initiative was found [2].

But a sustainable production is not only characterized by a reduction of material requisition and energy consumption [3]. At the same time, the reduction of wastage is important task. This requires a control of the produced work pieces [4]. By evaluating the work piece's quality, for example the geometrical dimensions, control variables can be derived and thereby the process could be regulated. The high output of work pieces and their complex structure generate high requirements on the measuring technology. Because of the fact that all surface features are formed in only one step, all of the features have to be controlled nearly at the same time. That means a holistic inspection has to be arranged in a way that features of all sizes are measured by measuring systems which accuracies are precise enough and measurement areas are big enough [5]. These high demands could be meet best with the optical measurement technology. This measurement method is contactless and enables complete detection of the work piece's surface in a very short time [6]. Besides laser scanning systems, fringe projection systems are already in use for production-related or even in-line measurements [7]. Due to the different scale of the work piece feature of sheet-bulk metal forming parts, a combination of systems with different resolutions is needed. To guarantee the appropriate accuracy for each work piece feature multiple fringe projection sensors with different measurement areas and accuracies has to be arranged. Thus a multi-scale measurement is possible [5].

In order to guarantee a high level of sustainability, the wastage has to be as low as possible. Therefore the rate of measured and controlled work pieces has to be as high as possible. The more work pieces are controlled, the faster deviations from the ideal are detected, and the faster variables for the process regulation could be derived. For such measurement not only the measuring systems and sensors have to be optimized and adapted to the sheet-bulk metal forming parts, also the measurement strategy has to be specified. Because of the complex surface and the high output-rate, measurement strategies, which are used in current in-line measuring systems, are not appropriate. The surface structures are in most cases not as complex as on

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sheet-bulk metal forming parts. Also the output-rate is incommensurable.

In this article an approach for the definition of a measurement strategy for a production-related multi-scale inspection of sheet-bulk metal forming parts is given.

2 CHARACTERISTICS OF SHEET-BULK METAL FORMING

2.1 Demonstrator work piece

In order to demonstrate the performance of the sheet-bulk metal forming a demonstrator work piece was worked out, which is shown in figure 1. For the development of the demonstrator work piece the hoped benefits of the new technology were analyzed. Leading work piece functions are integrated in a smaller number of single components due to the requirement on light weight construction. But also the requirements on the geometry and its accuracy are increasing. Thus technologies like bending or cutting cannot be used for the manufacturing of this new generation of work pieces. Therefore, function features like local tooth systems, carriers and butt straps have to be considered [1].

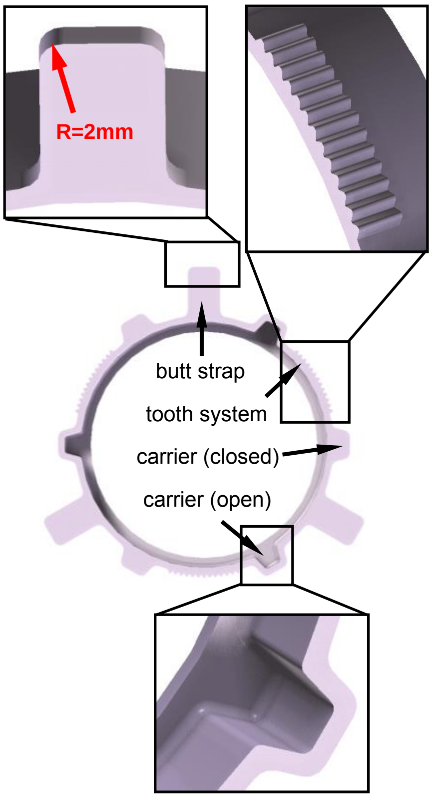

Figure 1: Demonstrator work piece

The tooth system symbolizes a very filigree feature. With a tip circle diameter of merely 0.4 mm, it is the smallest feature of the demonstrator work piece.

Material accumulation should be represented by a closed carrier. Thus the challenge is to transport the required material for a complete molding in the forming tool.

A second carrier in an open design simulates a depth-jump. Here the challenge in the production is to create a constant wall thickness and in addition the small internal diameter, which are in the size of 1 mm.

With a butt strap a possibility is given to check the capability of forming a comparatively long and thin feature. Challenging in this case is keeping the condition of the flatness. Furthermore the diameters of 2 mm at the end of the butt strap have to be molded correct. To guarantee this, a targeted material flow has to set up.

Each of the feature elements can be found three times in the demonstrator work piece.

2.2 Frequently manufacturing defects

Main characteristics of the sheet-bulk metal forming are three-dimensional material flow and material hardening. If these processes are not working proper, it can lead to characteristic defects. The complex geometry of the part features of the demonstrator work piece are designed in order to discover characteristic defects in case of an incorrect working forming process. Figure 2 shows some of the most frequently manufacturing defects.

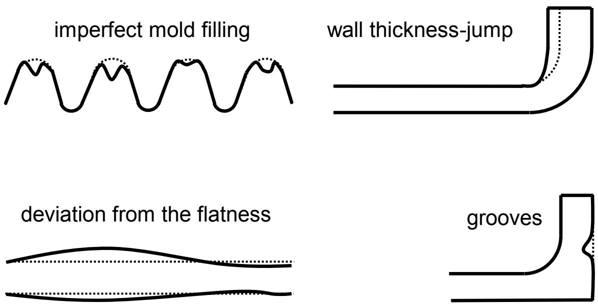

Figure 2: Manufacturing defects

Essential for a correct contour molding is a correct mold filling of the mold cavity. The material flow has to be set up in such a way, that material is dispersed ideal in the mold cavity and filled this completely [5]. Due to the complex geometry, the material flow has to be adapted to the particular volume of the work piece feature. To give an example, the closed carrier needs more material for a correct mold filling than the tooth system [8].

In contrast, there can be also significant surface deviations. As a consequence of too much available material, there could be variability of the sheet thickness. Equally, material hardening can differ locally. Both cases lead to a deviation of the flatness due to inserted stresses.

The frequently deviations of the ideal surface are essential for the development of a measurement strategy, adapted to the properties of the sheet-bulk metal forming. These deviations have to be detected and evaluated. In order to demonstrate the development of such a measurement strategy, an example of a diameter of 2 mm of a butt strap is used. Besides a simple geometry, a likewise simple defect characterizes this work piece feature as a proper example. In case of an incorrect working forming process, the diameter gets smaller or the roundness deviates clearly.

3 SELECTION OF AN APPROPRIATE MEASURING SYSTEM

3.1 Economic and sustainable importance of measuring systems

The selection of an appropriate measuring system is not only a question of technical requirements. Also economical and sustainable aspects have to be considered. Measurement results are information that is used as a basis for decisions. In case of the sheet-bulk metal forming, the result of the work piece inspection leads to a decision, if a work piece meets the specifications or not and if the variables of the forming process have to be changed. The less reliable the measurement results are, the more wastage is produced. Wastage of course is one kind of dissipation, which should be avoided absolutely. Because of this, when selecting a measurement system as defined by sustainability, the system should be as accurate and as fast as possible [3]. These properties lead to a high inspection rate with accurate results, which lead to a better control of the forming process. And thereby wastage can be avoided. But these properties require a higher monetary effort, which in turn reduces the economic benefit of the sheet-bulk metal forming technology. Therefore, the best agreement between requirements on sustainably and economic benefits have to be made [4].

To avoid a complex analyze, which systems could be the best agreement, the “golden rule of measuring metrology” can help. Georg Berndt developed in 1968 a rule for the selection of measurement systems. Therefore, the measurement uncertainty of the measurement system has to be known. The “golden rule” says, that the measurement uncertainty should be less than a fifth, better less than a tenth, of the tolerance width. If this minimum requirement could be met, it is assured that the measurement results are able to detect work pieces accurate enough. All systems that are conform with the “golden rule” can be consulted for the further selection of an appropriate measurement system [9].

3.2 Technical approach for selecting a measuring system

After preselecting the measurement systems, a clear selection based on a technical approach has to be made. The best measurement system is characterized by the detection of the work piece feature as fast as possible and as accurate as necessary. To test this capability of a measurement system, whether expert knowledge or a test procedure could be used. For the development of a production-related measurement strategy for sheet-bulk metal formed parts only little knowledge exists [5]. The capability of optical measurement procedures, especially fringe projection, was already proofed and is used for work piece inspection [10]. But there are different types of fringe projection systems with different resolutions and measurement areas. Both parameters have to be adequate large respectively accurate to detect a work piece feature holistically. To test this on measurement systems, the work piece feature is compared to an appropriate reference, from which the dimensions are known. If the capability of a measurement system to detect the reference correctly is proofed by repeat measurements, it can be concluded, that also the work piece feature is measured correctly.

This approach should explained by using the complex example of the tooth system. At first a reference for the contour of the tooth system has to be found. The micro-contour standard from the PTB [11] seems to be appropriate for this. It has very filigree surface structures similar to the tooth system and also the diameter on the standard is almost equal to the tip circle diameter. The contour-profile can be seen in figure 3.

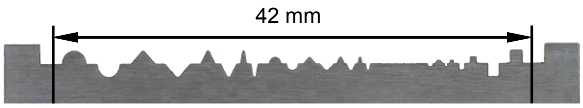

Figure 3: PTB micro-contour standard

The advantage of the micro-contour standard is that the dimensions are known very well and the contour is a bit more complex than the original contour. If a measurement system detects the micro-contour standard adequate accurate and fast, it can be concluded that also the tooth system is measured adequately. In the present case of the less complex diameter of the butt strap, the search for a reference is comparatively easy. As reference a segment of 90° of a cylinder a known diameter of 2.005 mm is chosen.

After selecting the reference to test the measurement systems, a selection of appropriate systems has to be done. For a fast and accurate inspection of sheet-bulk metal forming parts, fringe projection systems are already in use. After comparing parameters like resolution and measurement area, two different fringe projection systems are selected for the further investigations. System 1 has a resolution of 17 µm (lateral) and 1.0 µm (vertical) with a measurement volume of 13 x 8 x 3 mm³. System 2 has a resolution of 5 µm (lateral) and 0.3 µm (vertical) with a measurement volume of 4.4 x 2.8 x 1 mm³. For the detection of the reference as well as of the work piece feature, that has a dimension of 2 mm and, related to the tolerance DIN 2768m, a tolerance width of plus/minus 0.2 mm, both systems are appropriate. Also considered for the selection of measurement systems should be the “golden rule of measuring metrology”. In our case the tolerance width is 0.4 mm. That leads us to a minimum measurement uncertainty of 80 µm. Better would be a measurement uncertainty of 40 µm.

With both measurement systems 40 repeat measurements on the reference are done. Contrary to a measuring system analysis, the measurements are not done by different operators. Instead of this, the measurements are done under almost production-related conditions. Thereby one operator sets up the measurement system and the reference once and starts the measuring process again and again. This procedure is similar to an automatically work piece inspection.

For the evaluation of the results, normally in addition to the measuring values also the measuring cycle time is recorded. It reaches form the beginning of the measurement until the end of the evaluation. But both considered fringe projection systems do not have an automatically evaluation implemented yet. Because of this, the measuring cycle time is not recorded and considered for the further investigations.

For a fast and reliable selection of an appropriate measurement system, simple parameters can be used. The measurement results of repeat measurements of an ideal measurement system are not normally distributed, but are always the same value. Because of this, additional mathematical limitations have to be observed. It is not possible to calculate parameters like the standard deviation

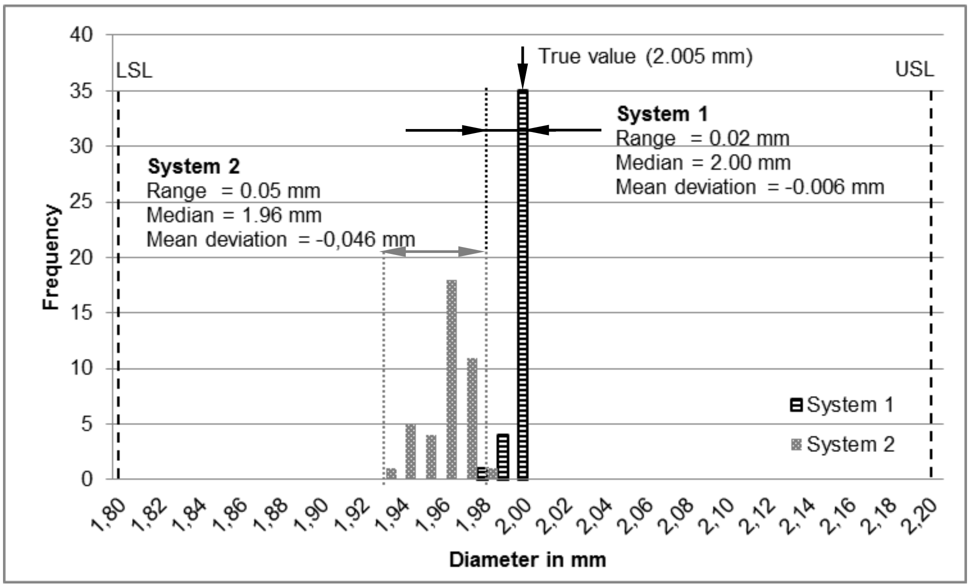

Figure 4: Measurement results and parameters

or the measurement capability index on a simple way. Hence, for the comparison of the measurement systems only simple parameters are considered. Firstly, the range of the measurement results is calculated. This parameter is the result of the difference between the highest and the lowest value. The parameter shows how good a measurement system is able to reproduce a measurement result under prevailing conditions. Next, the differences between each measurement result and the true value for the reference are calculated. From this follows how far a measurement result is away from the true value. The mean deviation is the result of the average of all differences. As a further parameter, the median is calculated also. This shows which result had been measured most. With these three parameters the more appropriate measurement system for the measurement task can be selected. The here described parameters are shown in figure 4.

4 DEVELOPMENT OF A MEASURMENT STRATEGY

If the parameters range, mean deviation, median and measuring cycle time are known for each work piece feature and measurement system, the measurement strategy can be defined. At first it has to be controlled for each available measurement system, if the minimum requirements of a work piece feature are reached. These minimum requirements have to be defined previously. The range should be at least a fifth of the tolerance width, less than a fifth would be even better. A minimum value for the measuring time depends on the production cycle time and the projected inspection rate. For a production-related inspection, the measuring time should be as close to the cycle time as possible. The higher the inspection-rate, the more work pieces can be controlled and the faster variables for the regulation of the production process can be generated. All measurement systems which reach the minimum requirements are compared directly. Though the intention is to find an appropriate measurement system for each work piece feature and thereby avoid using a system more often than it is available. If a measurement system has to be used more often than it is available, it would mean, that the work piece or the system itself has to be moved or positioned new during the inspection. Thus the measuring cycle time would increase. If the measuring time of a measurement system is significantly shorter than the process cycle time, a new positioning of a measurement system is possible without coming along with any disadvantages.

After selecting a measurement system for each work piece feature, the order of the measurements has to be defined. If possible, the measurements should be done parallel. But if more than one system is connected to the same computer, parallel measurements are not possible. Hence the measurement with the shortest measuring time should begin. If during this measurement a defective work piece feature is detected, the work piece inspection can be stopped and the calculation of variables for the process regulation can be started. Especially for inspections, which takes more time than the production cycle time, it is important, to detect defects as soon as possible. The more time elapses until a defect leads to the calculation of new process regulation variables, the more work pieces with the defect are produced. To increase the efficiency even more, the first measurement should not have the shortest measuring time, but also should inspect the most critical work piece feature. This would assure that the feature with the highest chance for a defect is controlled at first. That way saves important time, which can be used for a precise regulation of the sheet-bulk metal forming process, in order to reduce wastage. And this leads to a better sustainability again.

For a simple control of the selection of the measurement systems, an application based on an Excel-sheet was designed. The application tests, if a measurement system reaches the minimum requirements of a work piece feature and how good the system is in comparison to other measurement systems. With this support, the measurement strategy can be controlled.

In case of the example work piece, the selection of the measurement system is done as follows: The minimum requirement on the ranges, which should be smaller than a fifth of the tolerance width, is reached by both measurement systems. The measuring time is not considered. Due to the small range, the small mean deviation from the true value and the median, which is almost the true value, measurement system 1 is more appropriate for the inspection of the diameter of the butt strap. For the inspection, there are eight sensors of the same type available. Because there are only six diameters on the three butt straps of the demonstrator work piece, each work piece feature can be measured by one system. A movement or repositioning of the work piece or the measurement system is not necessary in this case. A schematic set-up of the measurement systems can be seen in figure 5.

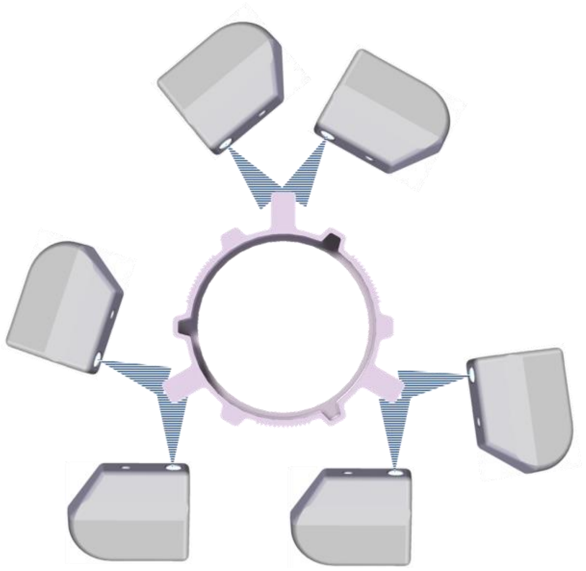

Figure 5: Set-up of the measurement systems

5 SUMMARY AND OUTLOOK

In this article the development of a production-related measurement strategy for the inspection sheet-bulk metal forming parts, in order of a fast and efficient process regulation, was described. For this, the characteristics of the sheet-bulk metal forming were described and their challenges for a production related inspection were explained. An approach for comparing and selecting measurement systems was shown as well as helpful parameters for a fast and simple decision making. The systematic way for selecting a measurement system and strategies for a work piece inspection is expended by the shown approach. Figure 6 shows the approach summarized in a flow chart.

To make the inspection even more efficient and thus increasing the sustainability of the sheet-bulk metal forming, in a next step the selection of an appropriate measurement system will be approximated to a mathematical optimization problem. This can be described and solved by algorithms. Thereby, the selection of a measurement system can not only be checked if the selected system reaches the minimum requirements, but also select the most appropriate system by solving the mathematical equations.

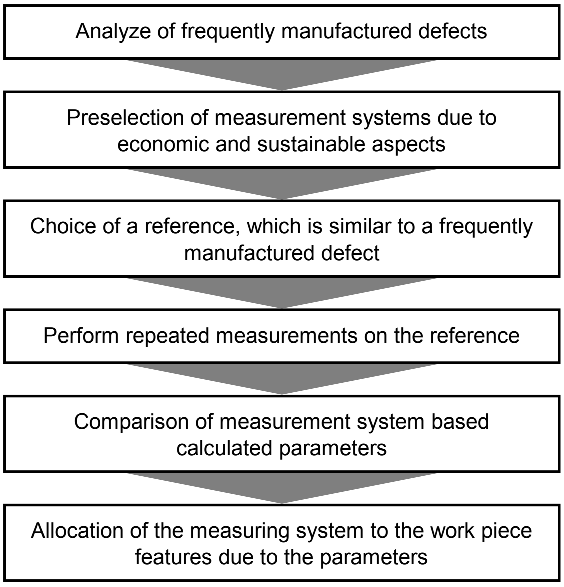

Figure 6: Flow chart

And as a further improvement, the defects during the production could be sorted by their number of appearance. The more often a defect appears, the better would be to start with the measurement of the related work piece feature. Thus it would be possible to detect the most frequently defects at the beginning of an inspection, which leads to a faster process control.

In Order to verify the advantages of the new measurement strategies several case studies have to be worked out and performed. Therefore sheet-bulk metal formed parts with different known defects will be inspected by several measurement system and using different strategies. With the proof of the effectiveness of the measurement strategies, the development of the sheet-bulk metal forming towards an industrial forming technology will be made a sustainably step forward.

6 ACKNOWLEDGMENTS

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