QUALIFYING MEASURING SYSTEMS BY USING SIX SIGMA

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Abstract: (250 Words)
The technology of sheet-bulk metal forming enables the production of complex workpieces with filigree surface structures in only a few forming steps. In order to provide a rapid and production-related workpiece inspection of not only large workpiece features, but also small features in an appropriate quality, a multi-sensor optical measurement system with different resolutions is required. Workpiece features of medium size can be measured by two types of fringe projection sensors. With a structured approach according to Six Sigma, which is based on the five phases design, measure, analyze, improve and control complex tasks are divided into smaller individual problems. In each phase the Six Sigma method recommends tools for solving the individual problems effectively. With the support of the Six Sigma guideline an exemplary sheet-bulk metal forming workpiece feature is used in order to qualify the two measuring systems for a production-related measurement. After defining the explicit goal for the investigations, a detailed analysis of the measurement process leads to a couple of relevant influences. These are input factors for the design of experiments. By a full factorial design, not only an influence of a factor itself, also the interactions between multiple factors can be detected. In the analyze-phase, these results are calculated by different statistical methods. To present the results in a comprehensible way several types of diagrams are used. The shown approach gives an example for a traceable and methodical way to qualify a measurement system for challenging measurement tasks.

Keywords: Six Sigma, Fringe projection, Evaluation of sensor performance, Sheet-bulk metal forming

1. INTRODUCTION

In times of increasing raw material costs, a consequent lightweight construction is getting more and more focused On the one hand, with lighter technical systems, less needed material guarantees a cost-efficient production. On the other hand, the energy consumption for the operation of the lighter system is reduced. These advantages lead to the demand for reducing weight. One frequent way to reduce the weight of a technical system is the integration of functions. Thereby, functions, for which at least one separate part is needed, are integrated in one common part. The resulting part exhibits a complex surface structure, which is often a combination of different features with filigree forms. By this increasing of the integrated functions, the overall number of parts can be reduced and thereby also the required material decreases. In order to benefit from the reduction of parts at the end, the production has to be able to generate the parts with their filigree and complex structures in an efficient and economical way. A forming process which forms the final contour in only a few steps would guarantee a fast and robust production. With the sheet-bulk metal forming such a forming technology is under development [1]. By its three dimensional material flow a selective forming of highly complex structures in only a few forming steps is possible [2].

In order to ensure a sustainable production as well as a further reduction of material requirements, a production related quality control loop is needed. By a control of the produced workpieces, deviations can be detected fast and hence, control variables for readjusting the forming process can be derived. Thus avoiding of scrap is supported, which assures an effective production.

Challenging for the set-up of a production related measurement system are the many different variants of the workpiece features, which can be realized by the sheet-bulk metal forming. The different dimensions of the complex structures require a multi-scale measurement [3]. With a multi-scale fringe projection system, consisting of 13 several measurement sensors which are different in their measurement area and resolutions, the requirements of a production-related workpiece inspection could be met best. Thereby for every possible feature dimension an appropriate measurement sensor is available [4].

Up to now the allocation of the several sensors to the different workpiece features is done according to the "golden rule of metrology". This was published by Georg Berndt in 1968 and says that the measurement uncertainty should be at least one fifth, better one tenth of the tolerance width of the inspected feature [5]. But if only this rule is considered, more possible allocations of appropriate measurement sensors could be arranged. An allocation then results on basis of experience and process knowledge. According to the small knowledge about the metrological detection of sheet-bulk metal forming parts, a structured approach for qualifying measuring systems for a fast and reliable workpiece inspection is necessary. Due to the methodical procedure, Six Sigma is used as a guideline for the further investigations.

2. A METHODICAL APPROACH BY SIX SIGMA

2.1 Definition of the problem and frame conditions

Six Sigma describes a library or a "toolbox" of different statistical and analytical methods. A structured guideline groups these methods in five phases: Define, measure, analyze, improve, and control. Abbreviated these phases are also often called the DMAIC-Cycle. For each phase, different "tools" are recommended and thus support for a structured problem solving is given [6].

At the beginning, the problem, which should be solved by the support of Six Sigma, has to be defined clearly. In this way an explicit goal can be derived, which will be traced in the following phases. In the present case the goal of the investigation is the qualification of different measuring sensors for the inspection of sheet-bulk metal forming parts. Particularly for feature dimensions between 0.5 mm and 2.0 mm, several measuring sensors of the multi-scale fringe projection system meet the “golden rule of metrology”. For an exemplary radius of 2.0 mm, which is tolerated according to DIN ISO 2768-1m, the tolerance width is plus/minus 0.1 mm. According to the “golden rule of metrology”, a measuring system for the detection of this radius should have a measurement uncertainty of at least 40 µm, even better would be 20 µm. These requirements are met by two fringe projection sensors. For the further investigations they are called Sensor 1 and Sensor 2. Sensor 1 has a measurement area of 13 x 10 x 3 mm³ with a resolution of 17 µm lateral and 1 µm vertical. Sensor 2 has a measurement area of 4 x 4 x 1 mm³ with a resolution of 5.0 µm lateral and 0.3 µm vertical. Being able to compare the ability of the sensors for detection sheet-bulk metal formed features, a test feature was selected. This is the 2.0 mm radius mentioned above. The feature belongs to a demonstrator workpiece, which represents the different forms and structures, which can be produced by the sheet-bulk metal forming technology. The radius is located on a 90° angle of a butt strap. Concluding the define-phase, the goal is specified to the investigated feature and sensors: Which measurement sensor is more appropriate for the inspection of the 2.0 mm radius and what are the ideal measurement conditions for this?

2.2 Analysis of the measurement process

In the following measure-phase, the measurement process has to be analyzed first. It is essential to know, how a measurement value is generated and under which conditions. By using a flow chart, the input and output factors for each process step can be analyzed and visualized. This tool helps to get a first overview of the process and to design experiments.

In order to select relevant input factors for designing experiments, the most important influences has to be detected. Therefore, a helpful tool is the cause-and-effect matrix. In this matrix the influences, which are analyzed by the flow chart, are evaluated on basis of their relevance for the measurement result. Thereby, criteria have to be defined which have to be met in order to measure precise enough to evaluate the result of the forming process. The evaluation of the criteria reaches from 1 (not relevant) to 10 (very relevant). In table 1, a cause-effect matrix for the current example is given.

Important for a measurement result is the detection of as many data points as possible. Thereby, a high resolution should be used. Ideally the gathered datasets should exhibit lacks of data points. In comparison to these criteria, less important is a large measurement area. Because of the previous selection of an appropriate measurement sensor of the multi scale fringe projection system, the basic requirements like the minimum size of the measurement area are already met. Also the measuring speed is considered in this previous selection and be seen as fast enough to meet the minimum requirements for a production related measuring process.

Now for every process input a number between 1 and 10 is determined, which says, how responsible an input factor is for meeting a criterion. Again 1 means that an input factor is not responsible for a criterion, 10 respectively means an input factor is highly responsible. This evaluation is supported by experts, who are experienced in handling and using fringe projection systems.

Table 1: Cause-effect matrix

	Evaluation of importance for customers (1-10)	7	7	3	9	3	
	Process Inputs	Many data points	No missing data points	wide measurement area	high resolution	fast measurement	**Sum**
1	Angle	3	7	7	3	1	121
2	Orientation	3	3	7	7	1	129
3	Sensortype	7	3	9	9	3	187
4	Reflection	9	9	1	1	1	141
5	Ambient light	7	7	1	1	1	113
6	Temperature	1	1	1	1	1	29
7	Vibrancy	1	1	1	1	1	29
8	Dirt	1	3	1	1	1	43
9	Filtration	3	3	1	3	3	81
10	Experience	7	7	1	1	3	119
11	Motivation	7	7	1	1	3	119
	Total	343	357	93	261	57	

The final evaluation of the complete relevance of an input factor is done by equation 1.

$$X = \sum E_{Customer} \cdot E_{Factor} \quad (1)$$

Whereas X is the Sum of evaluations for a factor, $E_{Customer}$ is the importance for customers and E_{Factor} is the the evaluation of the responsibly of a factor for meeting a criterion.

3. DESIGN OF EXPERIMENTS

3.1 Selecting relevant influences and parameters

By comparing the sums, input factors which are smaller than 100 are considered as not relevant enough for further investigations, because variations of these factors have only small influences on the final result. The relevant input factors, which are characterized by a sum over 100, are used as influence factors for a full factorial design of experiments. Constitutive to the seven relevant factors from table 1, influences are derived. The influences of experience and motivation of the operators are hardly to differ. Therefore, a common influence is defined for the full factorial design, called only Operator. The other factors are derived almost directly from the relevant input factors and are shown in Table 2.

Table 2: Relevant input factors

Influence	Variation
Surface	untreated; anti-glare spray
Illumination	room illuminated; shaded
Orientation	horizontal; vertical
Sensor type	Sensor 1; Sensor 2
Angle	0°; 22,5°; 45°; 67,5°; 90°
Operator	Operator 1; Operator 2

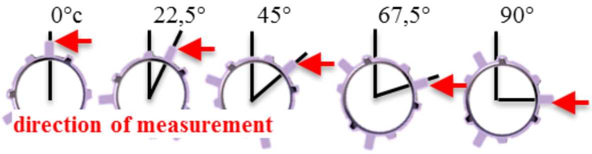


Fig. 1: Variation of the measurement angle

In the first column the influences are shown, whereas in the second column their variants are listed. The choice of the different variants results from supporting knowledge of experienced operators of fringe projections systems. Thereby, it was tried to select two realistic conditions, which can occur during measurements. The treatment of the workpiece's surface with anti-glare spray is a common method for fringe projection measurements to avoid directional reflections. By the variation between untreated and sprayed surfaces, the influence of the reflection properties on the measurement result should be detected. Also important is the influence of the illumination. Here a difference between room illumination and a shaded measurement room is made. The influence of the orientation of the measurement sensor is checked by a horizontal and vertical set-up. Next to the sensor's orientation, the workpiece's allocation is investigated. For this, a special workpiece carrier is installed, which can vary the position of the workpiece. Five different angles are projected for further investigations and explained in figure 1.

These influences and variations are combined by a full factorial design of experiments to 160 different configurations. For each configuration, 5 repeat measurements should be performed. That results a number of 800 measurements. With this full factorial design it is possible to analyze not only the influence of a parameter, but also interactions between the parameters.

3.2 Measurement system analysis

Before performing the experiments, the last step in the measure-phase is the measurement system analysis. This controls the fitness of the used measurement systems for the evaluation of the designed experiments. Therefore, similar features on three different workpieces are measured at least twelve times by both measurement sensors and by both operators. By statistical methods, different parameters of the measurement systems, like the repeatability and the statistical spread of the results, can be calculated. In the same way, interactions between the factors workpiece and operator can be detected. This parameter helps to make a decision if it is essential for the measurement result which operator measured which workpiece. Crucial for the fitness of a measurement system for evaluating a specific workpiece feature is the number of distinguishable categories. This declares how many clearly separated categories in the tolerance width exist in spite of every disturbing parameter, which are mentioned above. For the use of the measurement system for detecting data in order of deriving process improvements, the number of clearly distinguishable categories has to be at least five. In the current case, the minimum number of categories of five is not reached by any measurement system. Reasonable for this fact is the influence of the operator on the measurement system.

4. EVALUATION AND DISCUSSION

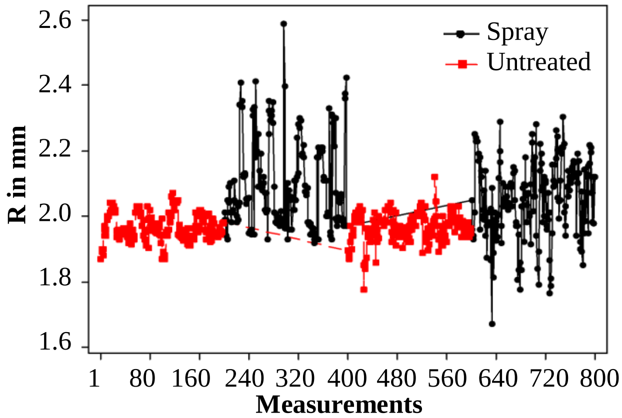


Fig.2: Overview over all 800 measurement results

After the measurement system analysis, the 800 designed experiments can be performed. The measurement results of the radius are collected for every measurement configuration. The analysis of the results is done with the support of the statistic software Minitab®. In addition to the designed experiments, a reference measurement is done by a coordinate measurement machine. A reference value of 2.005 mm for the radius in focus is detected. With the end of the measurements also the measure-phase ends and the analyze-phase with the evaluation of the results starts, according to the Six Sigma method.

At first the measurement results are visualized by diagrams. This approach gives a first overview over the 800 results and helps to recognize pattern. Some factors, which lead recognizable not to better measurement conditions, can be excluded from further evaluations. As it can be seen in figure 2, the spread of the results for the sprayed surface of the radius are clearly higher than the results for the untreated radius. Therefore, it can be assumed that on the one hand anti-glare spray removes directional reflections, but on the other hand the result of the radius is influenced adversely by the brought up powder layer. This effect seems to be significant adversely for workpiece features with a size of about 2 mm. Hence these results are excluded from the further evaluations.

For a further selection of the data, the variations of the different measurement angles are considered. In a comparison of the spreads of the results for every measurement angle, the smallest spreads can be found for an angle of 45° for both measurement sensors. As a conclusion, the best measurement conditions can be found for an angle of 45°. Therefore, only results for this angle are considered in the further evaluation.

To receive more details of the results, different statistical methods are used. With the help of the analysis of variance, the calculative standardized effect of the separate influences, as well as the interactions between the separate influences can be determined. The calculated standardized effects are shown in figure 3. On bases of the calculated statistical significance an effect has to pass a minimum of 2.0 to be relevant for influencing the result significantly. As it can be seen in the diagram, the influence of the sensor type on the measurement result is most significant. Next to this parameter, also the influence of the operator with a value over 2.0 is one more significant separate parameter. The other significant influences are interactions between two or three parameters. However, with the two significant separate influences of the sensor type and the operator a starting point for optimizing the measurement conditions is given.

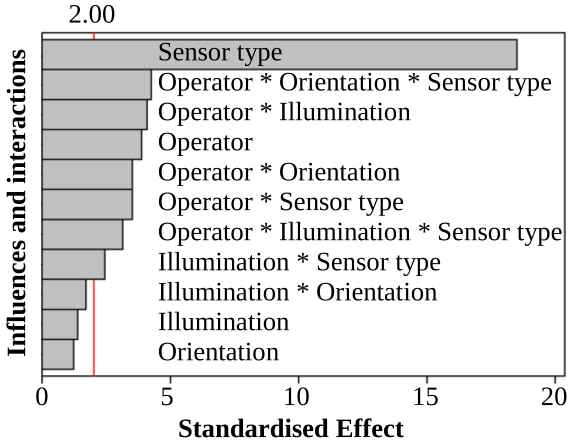
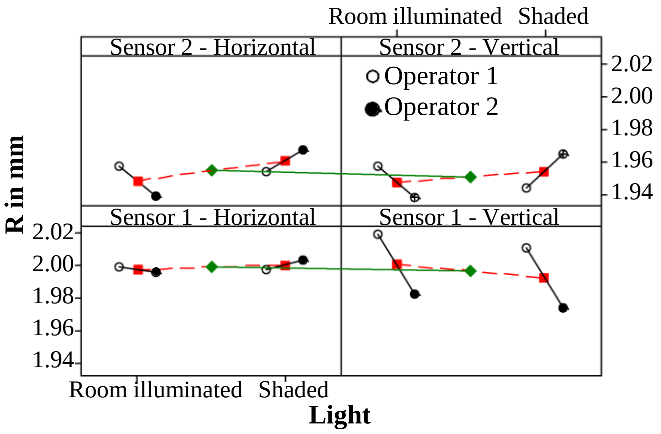


Fig. 3: Calculated standardized effects

In order to find the optimum of all considered measurement configurations for all parameters, a multi-vari-chart is used, which can be seen in figure 4. Therefore, the means of the results for the radius, collected under the different measurement conditions, are calculated and compared.



Field variables: Sensor type, Orientation

Fig.4: Muli-vari-chart

By analyzing the multi-vari-chart, the means for Sensor 2 are clearly not as close to the reference value for the radius of 2.005 mm then Sensor 1. Because of this, for the ideal measurement conditions Sensor 1 is chosen. If the sensors are orientated vertical, the means vary recognizable between both operators. Therefore, the ideal orientation is horizontal. The influence of the illumination leads only to a small variation of the means. But the mean for shaded measurements are closer to the reference value, hence this illumination type is added to the ideal conditions. The ideal surface properties are already chosen as not treated with anti-glare-spray. Alike the measurement angle was defined as ideal with an angle of 45°. Only the influence of the operator cannot be optimized. Because the measurements are not performed completely automatically, an operator is necessary. But with the decided ideal measurement conditions, the influence of the operator is reduced to a minimum.

5. CONCLUSION

The described approach according to the Six Sigma method the ideal measurement conditions for the inspection of sheet-bulk metal formed workpiece features were determined. Different measurement sensors could be qualified for the measurement task. By the systematical and analytical guidelines and the recommended tools for every phase of the DMAIC-cycle, meaningful results could be calculated and visualized in a recognizable way.

The shown results finalize in the analyze-phase. To perform the complete DMAIC-cycle, in the improve-phase arrangements can be defined, which ensure, that the ideal measurement conditions are always followed. Therefore, a Failure Mode and Effects Analysis can be used. In the final control-phase, the introduced arrangements can be checked for their effectiveness.

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