Potential of the Force Distribution Measurement in Deep Drawing Processes for Increasing the Process Quality

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***Abstract*—This paper presents experimental results of a novel approach for measuring the forces in forming machines. The basis for this approach is the development and arrangement of a modular measuring system which can be integrated between tool and ram of the forming machine. The modular character of the system allows it to be applied to any tool size and shape. A special focus of the application presented here is the recording of the local and temporal distribution of the forces and their significance with regard to component quality. In this way, it can be shown how changes in the process affect the distribution of force, for example by deliberately detuning the tool. In addition, statements on time and place can be derived from possible crack formation. In this way, the measuring system can be used for continuous process monitoring.**

***Index Terms*—smart manufacturing, smart production systems, sensor integration, process control**

I. Introduction

Even in times of 3D printing, parts manufactured by forming still represent the majority of large metal structural components. This technology has been used for many decades in the production of e.g. car bodies and washing machines. The increasing use of materials that are difficult to form, the trend towards more complex geometries and the increasing quality awareness of customers lead to a significant reduction in the process window within which good parts can be produced. Manufacturers take these circumstances into account with increased effort in tooling and maintaining constant process conditions. At the same time, prices for customers are rising in order to optimize margins.

In order to reduce the reject rate, there are numerous approaches for process control. The spectrum ranges from the dedicated use of local lubrication, the adaptation of drawing cushion parameters to the integration of actuators in the flange area. The suitability has already been discussed and proven in various publications (e.g. [1]). A basic prerequisite for intelligent and autonomous control, however, is a suitable process sensor system with which the process status can be adequately measured. The existing conflict here is always the balancing of dedicated, close-to-application and tool-bound sensors against machine-bound measuring instruments that are remote from the effect, but for this purpose only. In practice, a compromise is sought between the two in favor of economic efficiency.

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II. Deep Drawing and Its Failure Modes

If a hollow body is formed from a sheet metal blank by means of tensile/pressure forming or if a hollow body of smaller circumference is formed from a hollow body of larger circumference by tensile/pressure forming, this manufacturing process is called deep-drawing. The most typical process is deep drawing with a rigid tool, as shown in the following figure. In this process, the tool consists of a punch, a die and a blank holder, as shown in Fig. 1.

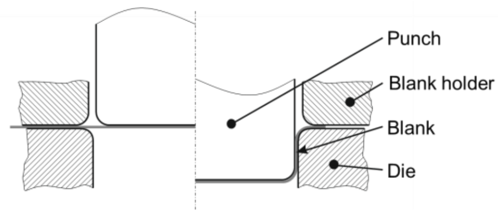

Figure 1. Schematic principle of deep drawing.

At the beginning of the process, the blank is clamped between the die and the working blank holder by closing the tool. As the tool is lowered further down, the blank is pulled over the rigid punch, whereby the drawn part bottom is first formed. As the drawing process increases, the retention force between the blank holder and die is no longer sufficient to inhibit the blank movement.

The quality of the forming process depends from several factors, which were already investigated and presented in several publications [2][3][4]. Especially the force distribution within the part layer as well as tribology are supposed to be the most important factors. The most important failure types for deep-drawing are wrinkling and tearing. Wrinkles can be differentiated into two different types. The first type, seen in Fig. 2a occurs in the flange area. The reason of these wrinkles are tangential compressive stresses in combination with a too low blank-holder force. Wrinkles of the second type (Fig.

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2b) occur in the free forming zone, which is located where the workpiece does not touch any active surface of the tool. Such an area can be found mainly between the upper die and the punch. Cracks, such as the one shown in Fig. 2c, usually occur in the area of the upper punch-edge and occur when the drawn part itself does not transfer the necessary forming forces. During plastic deformation of the blank the additional elastic strain leads to a certain springback of the part, as shown in figure Fig. 2d. [5]

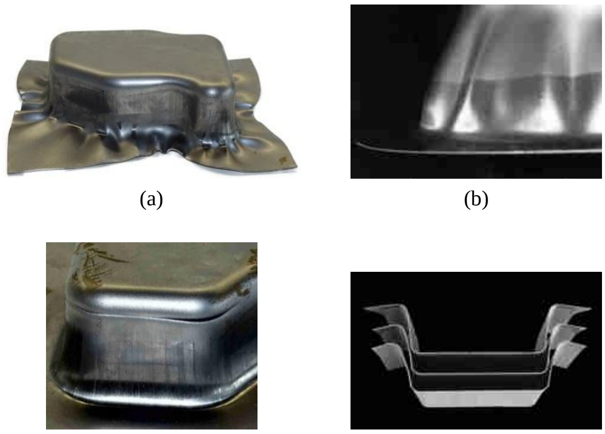


Figure 2. Typical failure-types in deep-drawing processes [6].

III. State of the Art

As already mentioned, the in-situ measuring of process parameters and quality indicators becomes more important, especially with special regards to the *Industrial Internet of Things (IIoT)* and Smart Manufacturing. Thus, many research activities were done considering the integration of different sensor types. A short overview is presented in [7]. Regarding the approach presented in the following section the force measurement will be focused.

In particular, the measurement of the punch force represents an already known approach of quantifying an important component of the process force. On the one hand, cracks can be detected [8], and on the other hand, by adjusting the blank-holder force a desired punch force profile can be achieved [9][10]. Due to the distance to the sheet layer and the lack of spatial resolution, the sole recording of the die cushion force by the integrated sensors is generally not a suitable approach to draw conclusions about the process state. A possible alternative is the use of the force-transmitting pressure bolts, which have a much tighter arrangement [11]. By recording the forces acting within the bolts, a much more precise statement can be made about the force distribution acting. The advantage of this system is the tool-independent sensor integration.

A tool-integrated approach is represented by the application of thin-film sensors in the workpiece contact area [12]. Piezo-resistive and wear-resistant coatings are applied to the tool surface, which allow local contact pressure and the effective temperature to be measured. A problem with this approach is the cost-intensive sensor integration at discrete points. For the monitoring of dedicated areas, however, this sensor form allows a high-precision detection of the local load.

IV. Measuring Approach and Experimental Setup

The approach presented here comprises a measuring system which is installed between the upper part of the forming tool and the ram of the forming machine, as shown in Fig. 3. In this way, all forces introduced into the forming system are recorded in their intensity and local distribution. The measured forces represent a superposition of the acting sheet holder forces and the forming forces, which are transferred by the punch or the sheet itself. As already indicated before, in addition to measuring the process-determining force distribution, indicators for possible cracks should also be detected in this way.

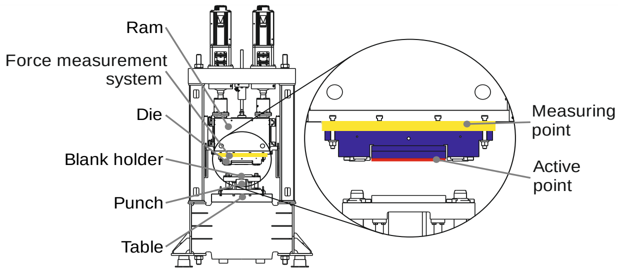


Figure 3. Experimental setup.

The measuring system itself consists of a combination of several identical individual modules. By interconnecting these modules as desired, almost all shapes and sizes of measuring systems can be constructed and applied to forming tools. Communication takes place on two levels. The information exchange between the individual modules is realized by an adapted I^2C protocol. The connection to the higher-level control system is variable. In addition to I^2C, other serial transmission protocols, Profibus or other fieldbus approaches are conceivable.

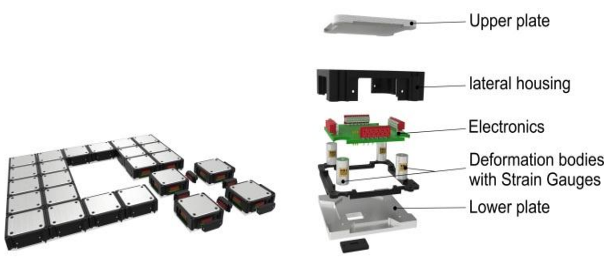
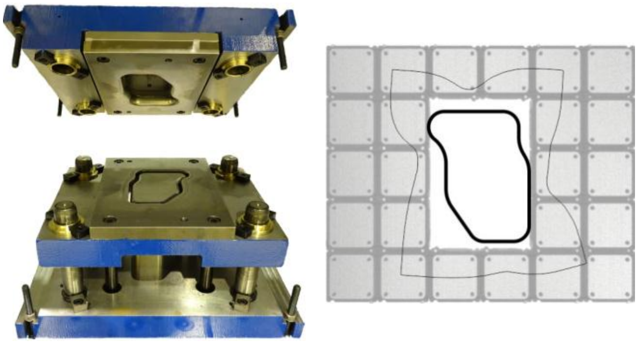


Figure 4. Modular concept of the measuring system.

The design of the individual measuring points is also modular. Four deformation bodies were dimensioned as force-transmitting components, which are clamped between two coupling plates. The electronics and housing elements were arranged in between. This approach allows the basic adaptation of the deformation bodies or the electronics and thus also the measuring range, without changing the geometry and the interfaces of the modules. Both modularization dimensions are shown in Fig. 4.



(a) (b)

Figure 5. Experimental tool (a) and part-system-orientation (b).

The experimental setup includes an experimental tool (Fig. 5a) which is used for the production of asymmetric cups with secondary form element. The tool has a base area of 430mm x 280mm and accommodates a standard sheet size of 220mm x 183mm. A servo-spindle test press was chosen as the forming machine, which has a four-point cushion based on gas springs and can achieve a nominal pressing force of 256kN.

V. Results

The experimental investigation focused three different use-cases:

A. Effect of Component Quality on Force Distribution Using the Crack as an Example

In order to test the thesis of the applicability of the system for crack detection and localization, a crack formation in the component was initially provoked by a slightly changed part position and a one-sided increase in the blank holder forces. Fig. 7 shows not only the process result but also the corresponding distribution of the forces involved and the temporal progressions. In addition, the reference process is shown without cracking for comparison purposes.

Both cracks were realized with the same system settings. A decrease in forces can be observed in the area of crack formation (top) on the basis of the temporal progressions. The reason for this is the reduced transmitted tensile stress in the sheet due to the crack. However, it can also be seen that the cracking is not identical despite the same parameterization. The process results suggest that the large crack (Crack 1) was originally formed from two partial cracks (Crack 2). Especially for the second part, it can be seen how both cracks are occurred during the process, since the reduction of the forces involved starts a little later on one side. In the other areas of the tool, the forces are largely identical.

Overall, it can be stated that cracks as well as the location and time of their occurrence can be recorded using the measuring system. This combination by a measuring system is not yet known in forming processes.

B. Effect of Process Detuning on Force Distribution Using the Example of One-Sided Distancing

In general, sheet holder distances can be used in the deep-drawing process to influence the gap between the die and the sheet. The force flow is shifted from the sheet metal to alternative force paths. This reduces the surface pressure on the sheet and thus the retention force, which favors a higher draw-in of the sheet.

The actual effect on the drawing result depends on the distance height, tribology and geometry, however, it can be expected that a change in the force distribution between ram and upper tool is associated with the insertion of distances. Fig. 7 shows the distribution and the course of the forces, after which a distance according to the fig. was introduced. Due to the concentration of the force flow, the measured forces increase at the upper modules. Since the geometry to be realized and the forces to be overcome do not change, the forces in other areas are expected to decrease accordingly for energetic reasons. In fact, this predicted effect can be seen in almost all other measuring points.

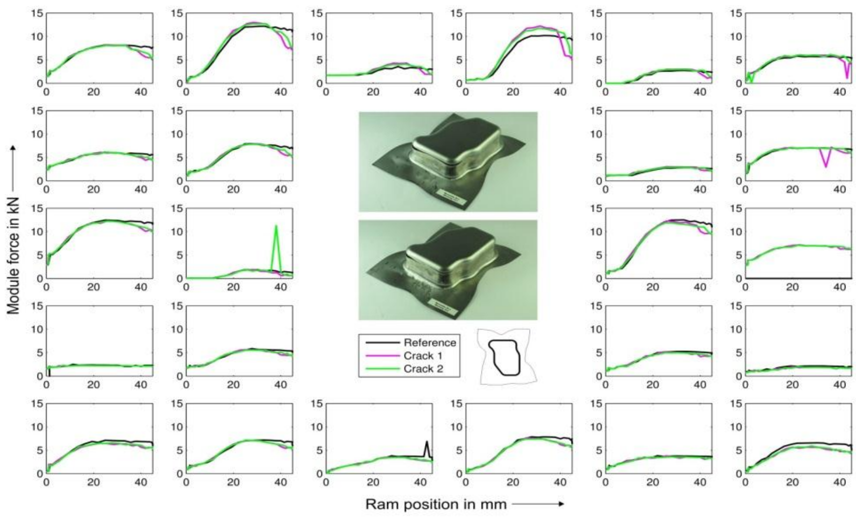


Figure 6. Measuring results for Use-Case A.

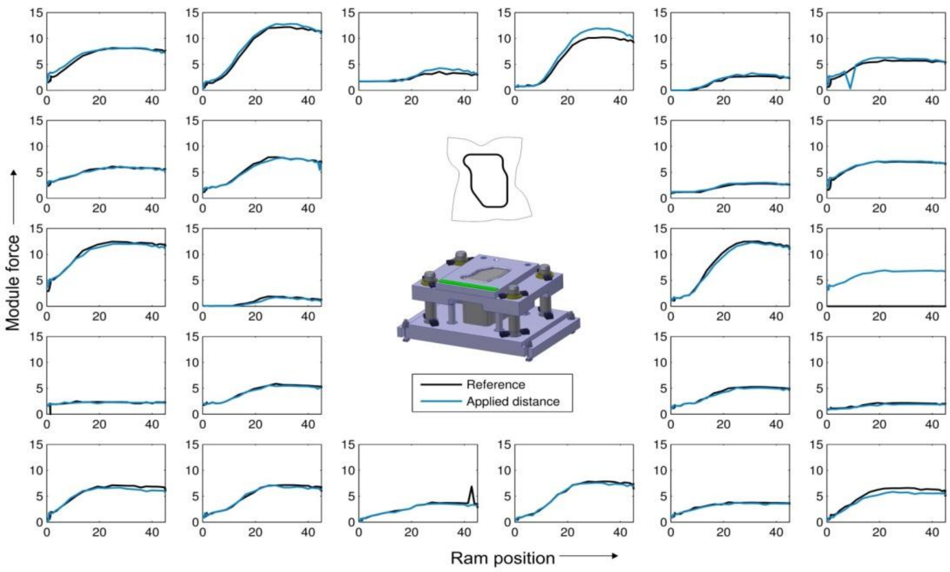


Figure 7. Measuring results for Use-Case B.

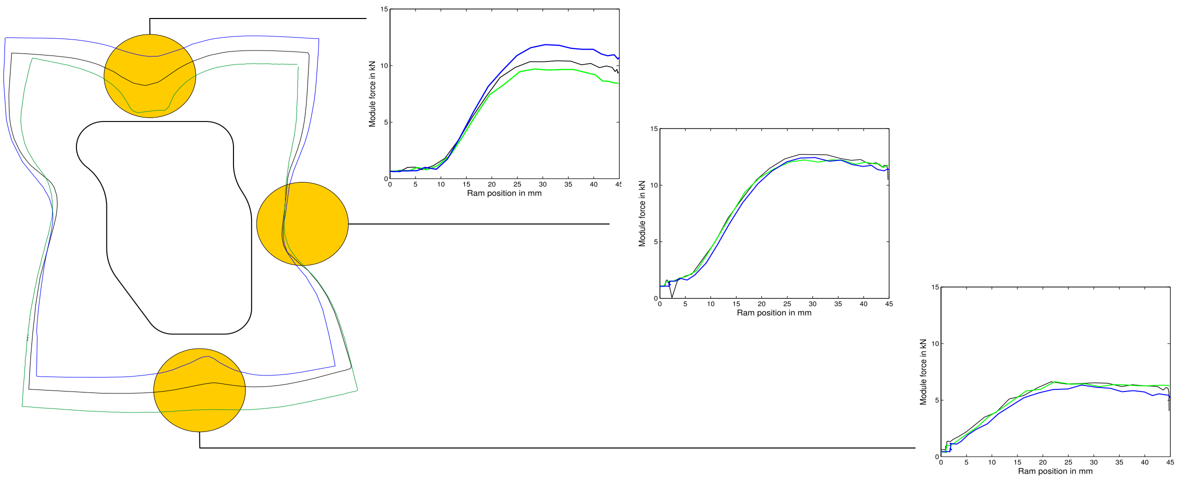


Figure 8. Measuring results for Use-Case C.

C. Correlation between the Sheet Position in the Working Layer and the Measured Force Distribution

By moving the plate within the working plane, the contact surfaces are changed, via which the force is transmitted. The relationships are complex due to the fundamental flexibility of the tool and the non-ideal tilting stiffness of the tool, so that the effective restraining forces do not remain constant. Fig. 8 shows for three different cases the contour of the sheet at the end of the process as well as the temporal force curves of selected measuring points. First of all, it becomes clear that the change in the original position also changes the target result. However, the underlying forces, which are measured above the respective points, also differ to varying degrees depending on the measuring point. On the upper side it can be seen how more force is transferred via the corresponding measuring point due to the larger area, while on the lower side there are significantly smaller differences in the force level, although there are also differences in the flange infeed. In contrast to this, no significant differences can be seen on the right side according to the same contact conditions. The reason for this is the relatively coarse local resolution of the modules compared to the sheet displacement, so that in some places similar forces are transferred, while in others more or less modules are increasingly involved. In principle, it should be noted that the measured force distribution alone does not allow any conclusions to be drawn about the flange draw-in.

VI. Conclusion

This paper presents measurement results of a new approach for measuring the process forces occurring in the forming process. Special focus is placed on the effect of changes within the process on the force distribution between ram and die. It could be shown that cracks in particular can be detected very well in terms of location and time by means of course-evaluation, which also promises application potential for other tool geometries. Changes in the force flows in the workpiece plane can also be recorded with the measuring system. At the same time, however, it can also be seen that the local resolution of the modules can limit the accuracy of the measured variable acquisition or requires a more complex evaluation of the available information. The correlation between changed force flows and other qualitative indicator variables must be investigated more intensively in further experiments. Future investigations will also focus on the closed-loop-control of force distribution using mechatronic actuators in the tool. To this end, the question must be answered as to whether and under what conditions force distribution can be used as an indicator of component quality.

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