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Experiences with inline feedback control and data acquisition in deep drawing

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Abstract

The increasing complexity of parts produced in deep drawing needs an enhanced process design, which results in different methods of the visualization of process windows. With these visualization methods, the process is usually designed to reach wide process window. Due to changing friction through rising temperatures in the tools, tool wear or batch to batch variations in the material, the process window is reduced again. Therefore new methods are needed to keep the process inside the process window. The paper deals with a possible approach of keeping the process inside these windows. The proposed approach tries to unite the measurement of possible influence factors like the batch to batch variation of material properties with a feedback control to eliminate the non-measurable influences. The measurement of the material properties is done by a measurement system based on eddy-currents, while the needed measurement for a feedback control is done with an optical system. Finally the paper will show the experiences with the proposed system, as well as it will show the prerequisites for such a system.

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Keywords: Deep drawing, Control, Material properties
1. Introduction

In deep drawing the part complexity is constantly rising due to new designs with increased complexity, therefore new efforts have to be made to keep the processes robust. Robustness of the processes can either be increased by narrowing the material and process specifications or by constantly monitoring the quality. While the first method significantly increases the production costs, the second method can be done without a cost increase. The paper will show a method of increasing process robustness by constantly monitoring and adjusting the process. As kitchen sinks are usually produced in small batches, every piece of scrap has a high influence on the overall scrap rate. Due to the small batch sizes, steady state production conditions might not be reached, due to a constant heating up of the tool. The temperature change in the tool is not only influencing friction, but also the material properties, as 1.4301 stainless steel has a temperature depend hardening behavior [1] due to its phase transformation from austenite to martensite. Therefore, the proposed system is necessary.

Nomenclature

<table>
<thead>
<tr>
<th>Szz</th>
<th>Sensor with number zz</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROI</td>
<td>Region of interest</td>
</tr>
</tbody>
</table>

2. Description of demonstrator part

For the demonstration of the proposed approach a series production kitchen sink is taken (Fig. 1). The kitchen sink is usually produced in three stages, starting with two drawing stages followed by one cutting stage. Possible defects for the kitchen sink are either wrinkle in the radii of the sink or cracks.

![Fig. 1. Demonstrator part.](image)

3. Measurements for control and data acquisition

During the process of manufacturing the kitchen sink, different measurements can be done, which either help to predict the outcome of the production process or directly measure the outcome. For manufacturing parts with a high quality, the material parameters have to stay in a certain range, which can be checked by eddy-current measurements. The part quality itself can be checked by measuring the produced part, for this one possibility is introduced later.

3.1. Material parameters

As the material is the main influence on the process, besides the process settings, the ultimate tensile strength and the yield strength are measured by the eddy current system proposed by Heingärtner [2]. The eddy current system is extended by a thickness measurement (Fig. 2) for an extended usability of the trained models. Besides extending the usability, the thickness itself has an influence on the process and has to be evaluated. On the right side in Fig. 2, the differences between different material batches for the same thickness can be seen. The difference of only 0.01 mm shows that the blank thickness can be adjusted well by the steel manufacturers.
Besides the varying thickness between different batches and manufacturers, the hardening behavior is highly dependent on the supplier. Fig. 3 shows that even in the range of the tensile test with maximum strain of up to 0.45, the curves are deviating. The kitchen sink itself has equivalent plastic strains of over 1.0, therefore the differences between the different suppliers will be even higher.

With the proposed eddy-current measurement system trained, the system is able to calculate the material parameters as first indicator of the achievable part quality. On the other hand, the system can neither determine the hardening behavior nor the surface quality, which influence the process. From the perspective of quality management, the system is good indicator for the material quality and therefore highly valuable.

3.2. Part quality

For the measurement of the part quality based on the draw-in, different sensor types have been developed in the past, e.g. laser distance measurement [3]. All these devices are usually directly integrated into the tool and therefore are only usable for one part. With rising computer power, the image processing can be used as a different approach. In the production of multi stage kitchen sinks, the part is usually relubricated between the first and the second drawing stage. Therefore, taking an image of the drawn part above this station does not influence the process. Also different sinks can be recorded with the same measurement system, which saves investment cost compared to the tool integrated systems. Fig. 4 shows a detail of the evaluated system of the draw-in measurement. In the evaluation
process, the image gets aligned to a reference image and afterwards the contour of the kitchen sink in an defined ROI (green in Fig. 4) is calculated. This contour is compared to the reference contour (red) of a high-quality part. The distance between these two contours is calculated at different positions and called sensor Szz. For the whole part 15 sensors can be defined.

![Fig. 4. Optical system image.](image)

With the draw-in measurement in place, first runs can be evaluated to quantify the allowed distance from the reference for the stable production of a kitchen sink. A production run with stable forces over the whole run, shows that the draw-in of the stable process fluctuates between ±3mm around the reference.

4. Data evaluation

The part is produced by the utilization of multiple blank holders, as it can be seen in Fig. 5. Sensors one to four are in the direct neighborhood of blank holder one, while sensors five to eight are close to blank holder 2. Sensors 10 to 12 are close to blank holder three, while sensors 13 to 15 are in the region of blank holder four. Even with the part being nearly symmetric except for the drainage (not visible but close to blank holder 3), all blank holders have different settings. By recording these settings and calculating the Pearson correlation coefficient, the influenced area of the blank holders can be determined.

![Fig. 5. Sensor positions.](image)
Table 1. Excerpt of Pearson correlations between blank holder forces and draw-in.

<table>
<thead>
<tr>
<th></th>
<th>S03</th>
<th>S08</th>
<th>S10</th>
<th>S13</th>
<th>BH 1</th>
<th>BH2</th>
<th>BH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank holder 1</td>
<td>-0.75</td>
<td>-0.35</td>
<td>0.25</td>
<td>-0.57</td>
<td>1.00</td>
<td>0.35</td>
<td>-0.17</td>
</tr>
<tr>
<td>Blank holder 2</td>
<td>0.06</td>
<td>-0.76</td>
<td>-0.79</td>
<td>-0.81</td>
<td>0.35</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>Blank holder 3</td>
<td>0.54</td>
<td>-0.43</td>
<td>-0.98</td>
<td>-0.66</td>
<td>-0.17</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Blank holder 4</td>
<td>-0.09</td>
<td>-0.56</td>
<td>-0.61</td>
<td>-0.98</td>
<td>0.58</td>
<td>0.87</td>
<td>0.68</td>
</tr>
</tbody>
</table>

The correlations in Table 1 show that the blank holder forces are mainly acting locally, as it would be expected. Especially the correlation of -0.98 between sensor 10 and blank holder three proves that. The high correlations in the input variables are due to a run with unequal, but constantly rising blank holder forces. This correlation in the input parameters is reflected in the generally high correlations between the blank holder forces and the sensor values. This also shows that the process itself is controllable through changing the blank holder forces.

5. Introduction to control

Fig. 6. Demonstrator part.

Controlling the process consists of two parts. First of all, the process itself has to be observable, while the second part is being able to control the process. Observability in deep drawing means to be able to measure the draw-in or a skid line [4] and to correlate the measurement with the quality criteria of the part. For kitchen sinks a detailed analysis is done by Harsch [5], which shows that the process is observable, even under the uncertainties of non-measured temperature and yield strength. For the controller itself the draw-in is calculated with the proposed system and used to calculate new forces for the four blank holder cylinders. In Fig. 6, a typical feedback control scheme can be seen with the influences acting on the process and the measured quality, which is fed back to the controller.

With the knowledge of the local acting blank holder forces, the following equations are used.

\[ \Delta F_1 = S02 \times K_2 + S03 \times K_3, \]  
\[ \Delta F_2 = S06 \times K_6 + S07 \times K_7, \]  
\[ \Delta F_3 = S10 \times K_{10} + S11 \times K_{11}, \]  
\[ \Delta F_4 = S13 \times K_{13} + S15 \times K_{15}. \]  

\( K_{\text{in}} \) in the equations are proportional parts of the control algorithm regarding the multiplied sensor error. The proportional constants are determined based on simulations with some adjustments in the press shop.

6. Controlled run

For the demonstration of proposed algorithm, the press settings are set to lower level than used for the production of the sinks. Therefore, the controlled run in Fig. 7 starts with a high draw-in error. Due to the measurement
principle, the draw-in error of plus 10 mm means that the blank ran too far and therefore the difference between the original blank and the desired draw-in is 10mm larger as it should be. All in all, the draw-in error is reduced in five parts to a value, at which good parts can be expected. A look at the force settings of the blank holder shows, that the forces are kept nearly constant from part sixty on. This stability in the forces can be directly seen in the constant draw-in error. Only an outlier measurement in part 66 produces a negative reaction of the algorithm for part 67 which is compensated again in part 68.

Fig. 7. Controlled run.

All in all, the proposed algorithm shows a stable behavior in the production line and is able to improve part quality.

7. Conclusion

The proposed data acquisition system helps to improve the part quality by using the virtually gained knowledge in a control algorithm, which shows an extremely stable behavior. Even without the control algorithm, the system is able to determine the part quality based on the draw-in directly after the first drawing step, which reduces the risk of scrap production significantly.

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