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Implementation of feedback control in kitchen sink production

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Abstract. The quality of deep drawn parts is affected by many different influences. These can be separated into material related, temperature related and tool related influences. In the case of the stainless steel used in kitchen sink production, the temperature not only influences the friction but also the material properties. Therefore, a continuous monitoring and adjustment of the process is needed. The present paper shows a possibility of monitoring the current state of the part in combination with a control system for the adjustment of the press to compensate for non-measurable influences. The proposed monitoring system consists of an optical measuring device for the part state, as well as a non-destructive material testing system for the determination of material properties. The control system uses the blank holder forces as actuators. Also, the performance of the proposed system in the production line is shown.

1. Introduction

In kitchen sink production, small batch sizes are produced. Therefore, the process is continuously changing, as the temperature hardly reaches a steady state. The changing temperature not only influences the friction, but also influences the material. The material is 1.4301 stainless steel, which has a highly temperature dependent behavior. With small batch sizes, not only the variation of the temperature has a large influence, but also the batch to batch variations of the material, since the process has to be adjusted for every batch.

The adjustment of the process can either be done by a machine operator or by a control system. The presented paper deals with the implementation and adjustment of such a control system. In the past, different solutions were presented that used actuators in the tool [1][2] instead of using the machine settings directly. Therefore, the presented solution will use the process settings along with an optical measurement system to measure the draw-in. The solution can be extended by using an eddy-current measurement system for the measurement of material properties as presented in Fischer et al. [3].

2. Used Measurement system

For the adjustment of the process, it is necessary to be able to observe the current state of the part. Thus, a suitable measurement system is needed. In the literature, different tool based systems are discussed [4], which have the disadvantage of being fixed in the tool without having the flexibility of taking measurements at different points or different parts with the same system. For measurements at a different point, the tool has to be reworked. For this reason, an optical system is designed which allows for a high degree of flexibility in the measurement points.

The measurement principle of the optical system can be seen in Figure 1. Above the relubrication system, an image is taken and is aligned to the reference image. After the alignment, the contour of the current image (green contour in the images) is determined and the distance to the reference contour (red) is computed along predefined lines (yellow arrows in Figure 1 labeled by Region of Interest (ROI) and sensor number). The resolution of the images results in a conversion of 1 pixel to 0.28 mm. The alignment is necessary, as the grippers on the robot do not allow for a reproducible position above the relubrication station. For the alignment, two lines are fitted to the edges of the kitchen sink itself, which enables the computation of a local coordinate system. Based on the deviation between the local coordinate system and the coordinate system in the reference image, the image is translated and rotated to compensate the gripper position.

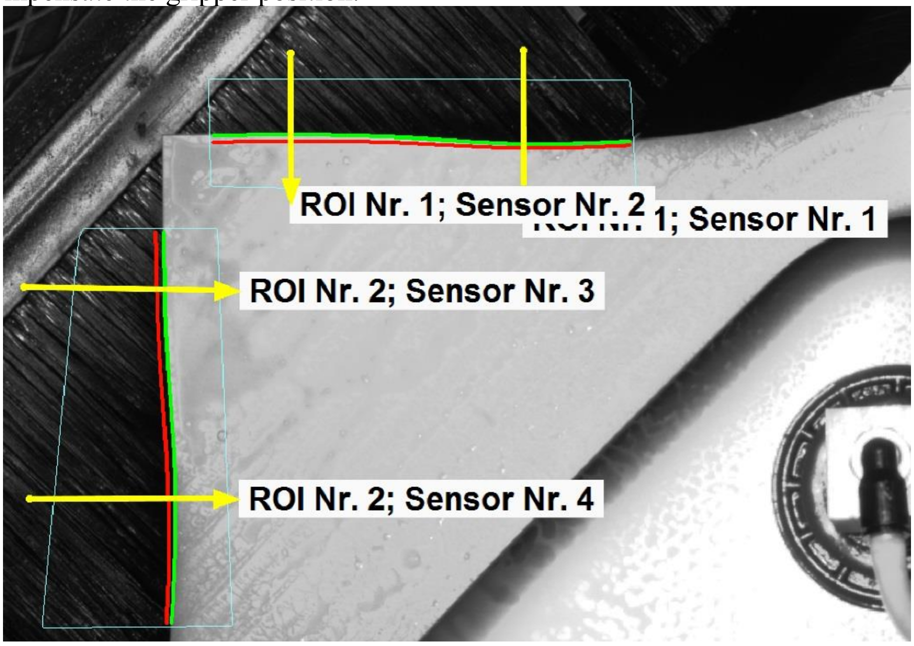

Figure 1. Draw-in measurement principle

The measurement of the middle of a large batch shows that the process itself is stable. Figure 2 shows that the draw-in of the two hundred parts lies around +/- 2 mm of the reference, which results in a good part quality. The reference for the showed run is the first image, as the process is already in the steady state. The mean value of the deviation over all sensors is -0.18 mm and the standard deviation is 0.95mm which supports the assumption, that the first measured part can be taken as the reference. Also, part to part variations can be identified, as well as a zone around part 20 which could be improved by applying control, as the draw-in is nearly three millimetres away from the reference for some time, due to an unknown influence. Experience shows that a draw-in deviation of 5-7 mm, already results in a defect part.

All in all, the proposed measurement system shows a sufficient measuring accuracy to determine if the part quality is good or if the process settings should be changed. Already for the continuous measurement of the parts, the communication with the press, which is explained in the next section, has to be implemented.

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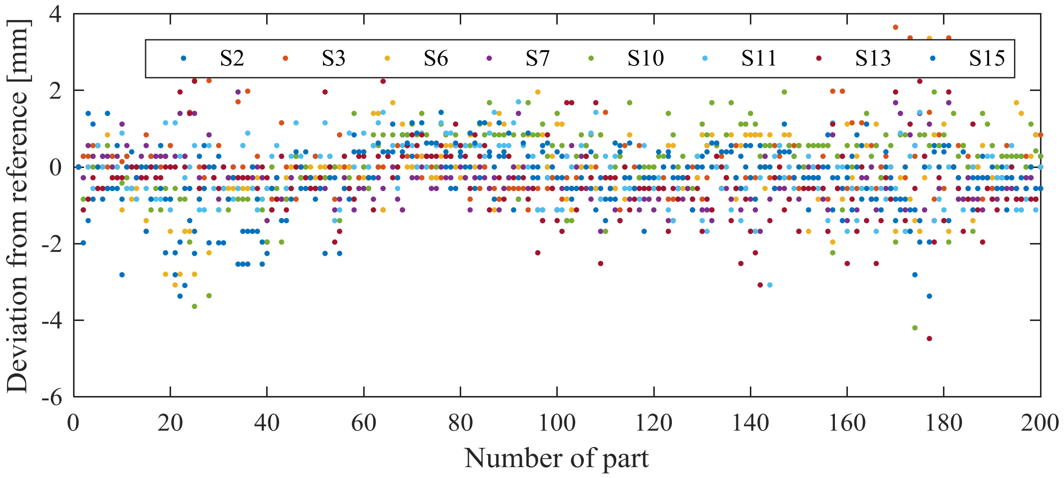

Figure 2. Draw-in measurements of stable process

3. Implementation

The first step in implementing the measurement system, as well as the control system, is the analysis of the current situation.

3.1 Press settings and other prerequisites

The demonstrator part is produced on a hydraulic press, which has the advantage of a high adjustability of the process parameters. The kitchen sink is produced in two steps, as the shape is mainly generated in the first step (the part after the first step is shown in Figure 3), the control will focus on this step. Besides the adjustability of the forming speed, the hydraulic press allows for multiple blank holder forces.

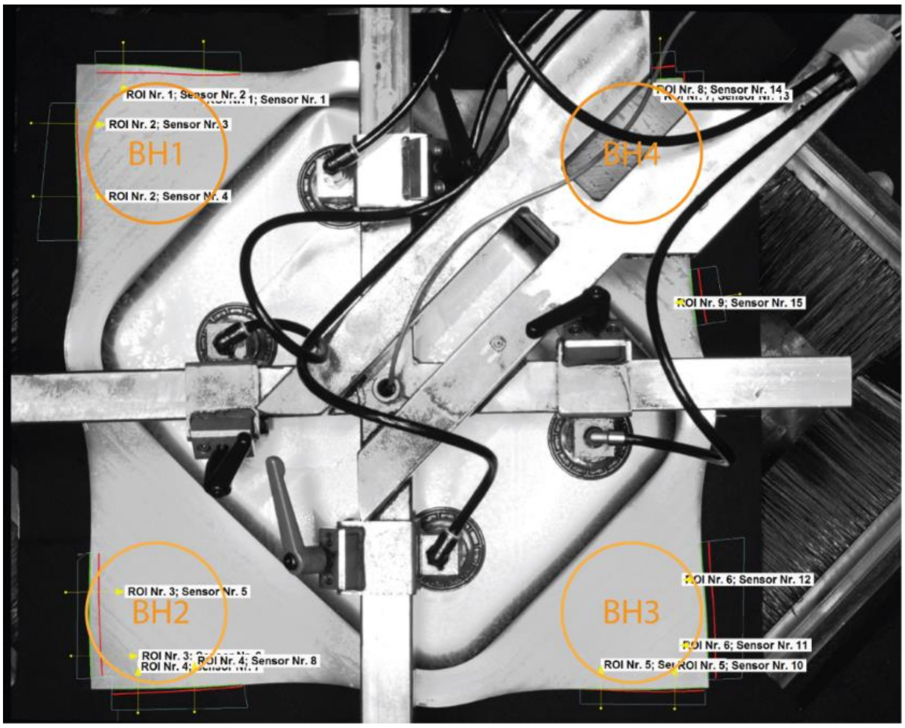

Figure 3. Blank holder system

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Besides the four locally acting blank holders shown schematically in Figure 3, a fifth blank holder is present. The fifth blank holder acts globally instead of locally. Besides only setting five forces for the five blank holders, the forces can also vary over the distance travelled by the forming punch.

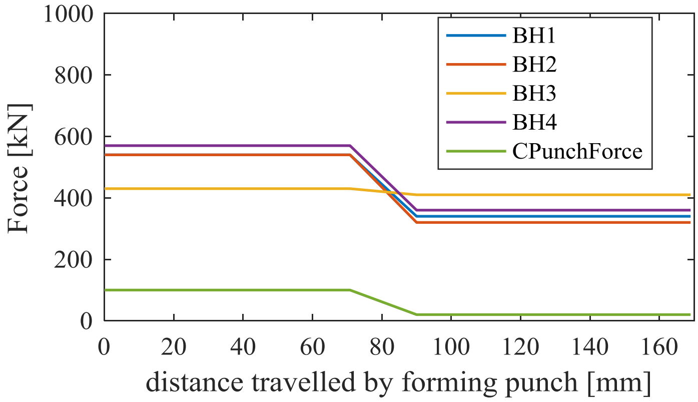

Figure 4. Process settings

In Figure 4, one possible setting for the five forces can be seen, with BH1 through BH4 being the local blank holders and the globally acting one is called CPunchForce. Besides the possibility of changing the blank holder forces, a trigger signal for the optical measurement system is needed. The trigger signal is necessary to measure all parts at the same robot position.

3.2 Implementation of the communication

The implementation of the control system for an academic trial system should be completely detachable from the regular running system. Therefore, different additional systems are installed (see Figure 5).

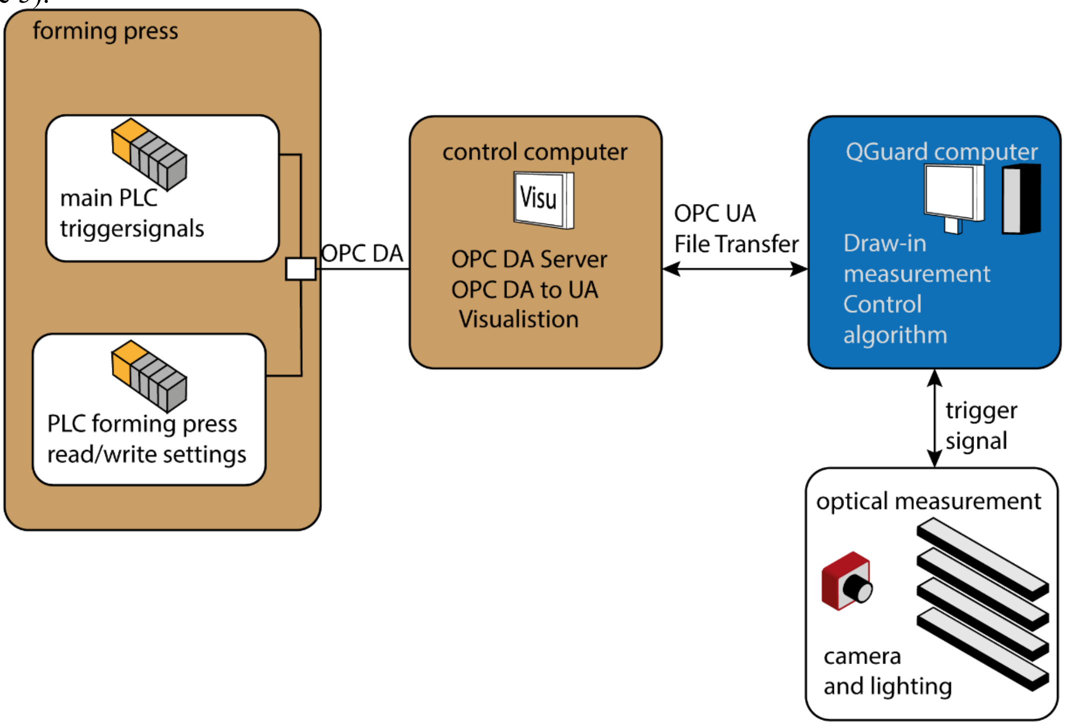

Figure 5. Implementation scheme

Usually, the position of the part and the settings can be checked and changed in the visualisation part of the machine. For the control system, the same communication channel is utilised. As the original communication is done by OPC DA (Open Platform Communication Data Access) which is extremely sensitive on the calling operations system, for the additional system, the protocol is changed to the more robust OPC UA (Open Platform Communication Unified Architecture)). Also, the measurement system is directly attached to the computer with the control algorithm to minimise communication efforts. With the implemented system, control runs are possible.

4. Controller design

In an earlier paper [5], a basic approach for the design of an control algorithm based on metal models is shown. The paper assumed that the process of producing kitchen sinks can be controlled by adjusting the overall force and the blank position. As changing the blank position would result in a further communication interface, this actuator is dropped. With only the overall force left, the control algorithm was chosen according to equation 1.

$$\Delta F_t = \frac{(S02*K_2+S03*K_3+S06*K_6+S07*K_7+S10*K_{10}+S11*K_{11})}{6*4} \tag{1}$$

$$F_0{}_{k+1}^{BH1} = F_0{}_{k}^{BH1} + \Delta F_t \tag{2}$$

$$F_{90}{}_{k+1}^{BH1} = F_{90}{}_{k}^{BH1} + \Delta F_t \tag{3}$$

The gain K for each sensor position is chosen by linearizing the simulation based meta models for the sensors at the nominal value. The change in the total force is calculated for each sensor and then averaged. The division by four is needed, as the force should be changed equally for blank holder 1 through 4, according to the equations 2 and 3. The used sensors are chosen to accord for three areas of the draw-in line, while the measurement of the forth was not possible with the settings at hand. The additional available sensors would only lead to a further averaging and therefore, they are not used in the current state. The globally acting force CPunchForce is not changed, as it is already set to the minimum possible force with which the press is still working.

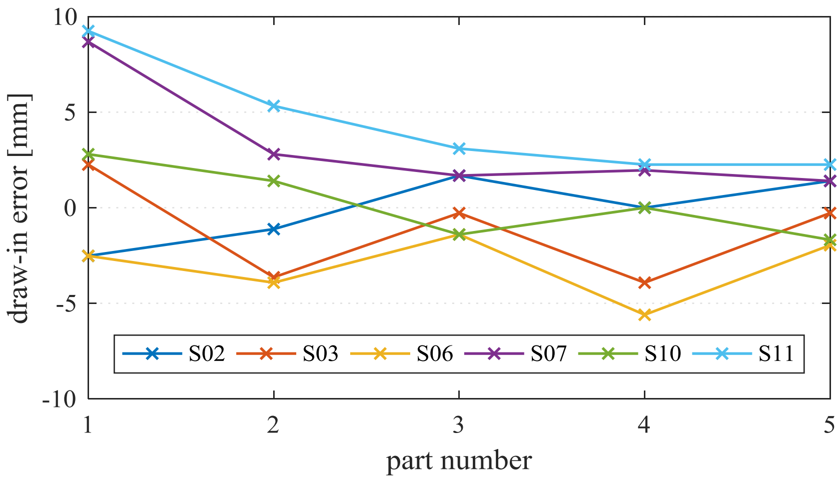

Figure 6. draw-in error of controlled run with the first algorithm

The result of a controlled run with the proposed algorithm can be seen in Figure 6. The run starts with the force values of all four blank holders reduced to 80% of their production run values. This reduction leads to a high draw-in error at the beginning of the run, resulting in a step function for the draw-in controller. In five parts, the controller is back to normal level in the draw-in of the shown sensors.

But the approach of changing only the total force is limited to global effects. With the provided tooling, as well as the asymmetric blank holder forces, the approach of changing the global force based on a few draw-in sensors leads to parts with defects similar to the one in Figure 7.

Figure 7. defect part

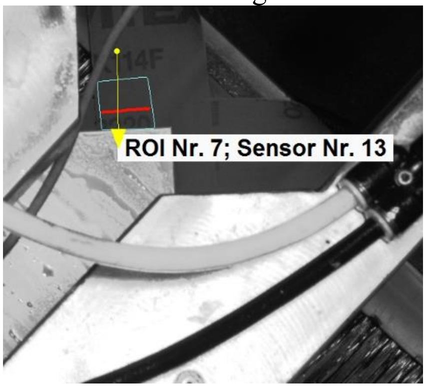

Figure 8. draw-in of defect part

The defect is also detectable in the draw-in. While nearly all draw-in sensors show a good agreement with the reference, the sensor in the upper right corner shows a significant deviation (Figure 8) and is not measurable due to the draw-in edge laying outside the region of interest. The defect is in the nearby corner of the sink. With the knowledge from these control approaches, a new controller design is developed.

The new control approach focuses on minimising the local draw-in errors by using the local blank holder forces. For adapting blank holder four, two further sensors (S14 and S15) are introduced, which are already marked in Figure 3. Additionally, the region of interest for sensor 13 is enlarged to cover a wider range of draw-in deviation.

The change of the force settings of a blank holder is now only depending on the local draw-in errors, as the equations 4 through 7 show.

$$\Delta F_{\mathrm{BH1}} = \frac{S02*K_2+S03*K_3}{2*4} \tag{4}$$

$$\Delta F_{\mathrm{BH2}} = \frac{S06*K_6+S07*K_7}{2*4} \tag{5}$$

$$\Delta F_{\mathrm{BH3}} = \frac{S10*K_{10}+S11*K_{11}}{2*4} \tag{6}$$

$$\Delta F_{\mathrm{BH4}} = \frac{S13*K_{13}+S15*K_{15}}{2*4} \tag{7}$$

Equations 2 and 3 are still the valid update routine, except that ΔF_t is replaced by the local change ΔF_{BH1}. The controller gains K themselves do not change, but they are again divided by two for averaging and by 4 for the approximating the local behavior. The gains are unchanged due to a FEA model, which is unable to predict the local behavior. For an increased stability of the system, the change in the blank holder ΔF_{BHx} is limited to 20kN. With the new control design in the place, a controlled run has to be done to evaluate the performance.

5. Controlled run

The new control algorithm is again tested by starting the process with blank holder values that are reduced by 20% compared to the current production values. The first part with the lowered blank holder forces is 54, as the measurement system was not reset. The development of the draw-in error in Figure 9 shows, that the algorithm needs about four parts to bring the draw-in back to the nominal value. With the draw-in at the nominal value, the occurrence of wrinkles is avoided as well.

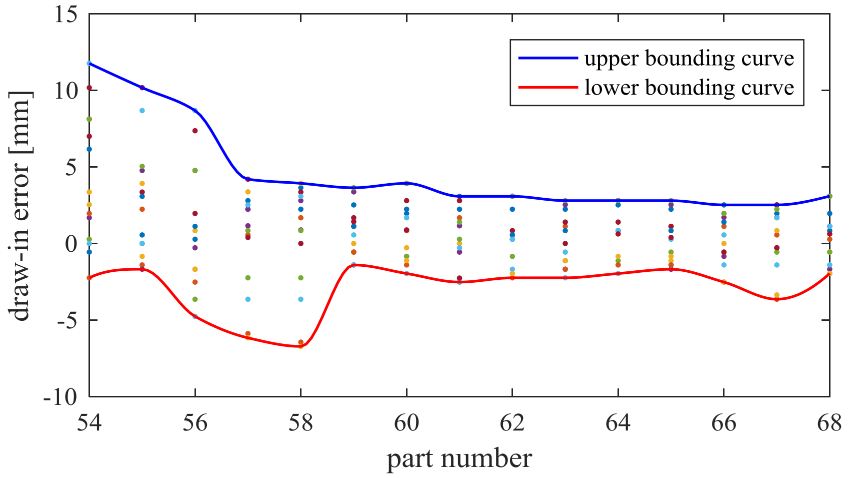

Figure 9. draw-in error of controlled run

The development of blank holder forces, shown in Figure 10, shows that the draw-in at the nominal value results in constant blank holder forces, as expected. A closer look at the development also shows the limitation of the change in the blank holder forces between two parts. A further stabilization of the process behaviour could be introduced if the force is only changing when the draw-in error lies outside a certain boundary.

All in all, the controlled run shows, that the controller is able to reduce the draw-in error, as well as the associated defects.

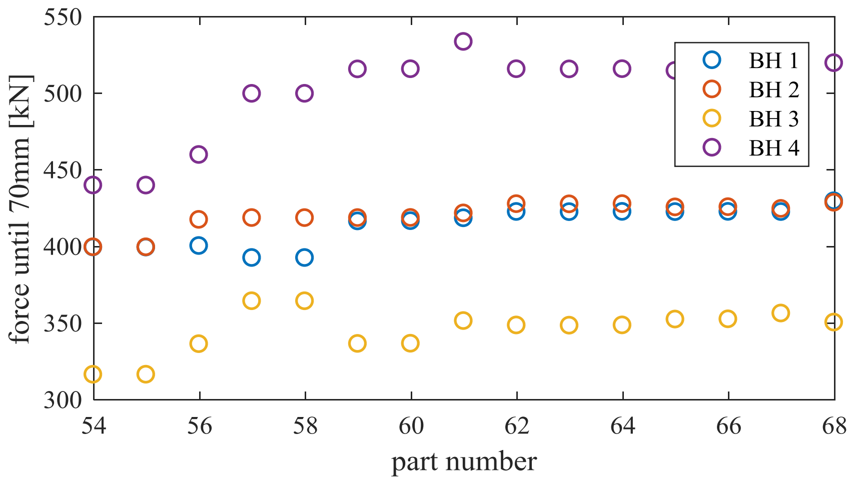

Figure 10. development of forces during controlled run

6. Conclusion

The implementation of a control algorithm needs a proper measurement system, as well as good knowledge about the process and the production line. The knowledge about the process can be gained by variant simulations, which also allow for a first parameter set for the control algorithm. With the first parameter set already reducing the draw-in error significantly, the behavior of the control algorithm could be improved in the future by adapting the gain factors based on process measurements.

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