Materials Research Proceedings 28 (2023) 2081-2090 https://doi.org/10.21741/9781644902479-223

Conception of a multivariable product property control for punch-hole-rolling

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Keywords: Property Control, Forming, Punch-Hole-Rolling, Sheet-Bulk Metal Forming

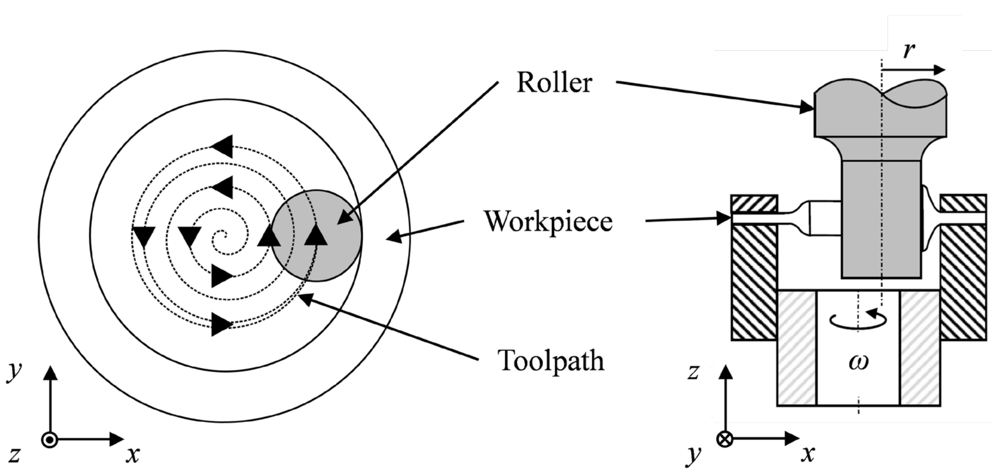
Abstract. Process controls are getting increasingly more common in forming. Nevertheless, they are not suitable to achieve consistent quality when dealing with varying process disturbances. Differing properties of the raw material and other external influences like temperature variations and vibrations make it hard to achieve the tightly specified tolerances needed in today's production environment. Product property controls represent a solution for these difficulties and create the opportunity to integrate additional functionality into the product and the process. In this project, the implementation of a multivariable product property control is investigated using the example of a recently developed process, called punch-hole-rolling. It is targeted to control product properties such as the collar height and the hardness on the inner surface. It has been shown in previous publications that it is possible to control the collar height in 1.0338 by carefully choosing suitable process parameters. In recent works the possibility was presented to control the hardness by changing the same parameters, using the TRIP steel 1.4301. The publication at hand aims at proving the feasibility of the multivariable product property control by reviewing the previous results for 1.4301 and proving that it is possible to control the collar height and the hardness on the inside of the collar simultaneously. Further, a concept is presented for the implementation of such a control.

Introduction

In recent years resources have become increasingly scarce. In 2022, steel prices in northern Europe and especially Germany spiked at two times the rate it had, just three years ago [1,2]. Simultaneously, the price of energy has almost tripled in the same time period [1]. Furthermore, environmental protection is becoming increasingly more important as new legislation for example in Germany proves [3]. Reducing the material and energy consumption is an easy way to improve the human impact on nature. Given the current circumstances it is obvious that this also brings major economic benefits. Simply reducing the consumption is not an option in most industries, however, as this would lead directly to a proportionate reduction in production, which is neither economically viable nor desirable. Therefore, other solutions need to be found. One option is to switch from production processes which are less material and energy efficient to those that are more efficient. Here, forming processes have great advantages compared to cutting processes. They have a higher material utilization and use less energy on average [4]. Nevertheless, there are many products, which can not be produced by forming. Either the geometry cannot be formed or the products require tolerances, which cannot be produced by conventional forming processes. A great example for this type of products are bearing seats. Due to the great advantages of forming processes it is senseful to develop new processes to overcome these challenges. In the case of bearing seats, punch-hole-rolling is a proposed solution, which is a recently developed forming process that is presented in more detail in the following chapter. Another option to increase the resource efficiency of production processes is to reduce the proportion of parts that have to be scrapped. Fluctuations in the material can easily lead to product properties out of specification, especially in forming processes. Controls enable the compensation of disturbances, but conventional process controls in forming are not able to detect the specific deviations, and many conventional processes do not have the degrees of freedom to counteract them. In their work, Allwood et al. presented product property controls in combination with suitable processes as a solution for these problems [5]. With this technology it is also conceivable to control more than one property at a time and further enhance the advantages of forming processes.

Punch-hole-rolling.

Punch-hole-rolling is a process, which was recently developed at the Institute for Production Engineering and Forming Machines (PtU) at the Technical University of Darmstadt in cooperation with the Institute for Applied Materials (IAM) at the Karlsruhe Institute of Technology. It is a forming process which is best specified as sheet-bulk metal forming, according to the definition by Merklein et al. [6]. Additionally, the process is an incremental forming process. Knoll et al. classified the process as pressure forming due to the acting stresses and as a rolling process due to the main tooling used [7]. Punch-hole-rolling consists of two separate steps. The first step is the punching step in which the starting hole is generated. Unlike the name may suggest, the starting hole does not have to be punched. Previous tests showed that drilling is a suitable alternative. The two steps of the process also do not have to be performed directly after another. The second step is hole-rolling. In this step, the roller is inserted into the hole in the workpiece, which was created by the first operation. After that, the tool performs a spiral movement, in which the material of the sheet metal is pushed outwards and to the top and bottom. This movement enlarges the hole, simultaneously forming a collar on both faces of the metal sheet. Ideally both sides of the collar are mirrored copies of each other. In Fig. 1 the punch-hole-rolling process is pictured. On the left side of the figure, the process is shown from the top and the spiral movement of the roller is marked. On the right side of the figure, the process is shown from the front. The sectional view of the workpiece allows to see the forming of the collar. On the right-hand side of the workpiece the collar is pictured almost in the final stage, while the left-hand side shows it shortly after the process started.



Fig, 1. Sketch of the punch-hole-rolling process, including the relevant process parameters [8].

The process can be influenced by changing the starting hole diameter in relation to the diameter of the finished product, the radial feed rate and the rotational speed. With these process parameters the two product properties of interest, collar height and hardness on the inner surface of the collar, can be influenced. The specific relations will be discussed in the subsequent chapters. In Fig. **2** the setup for performing the punch-hole-rolling process is shown. A conventional lathe is used for this purpose. Therefore, the sheet metal is mounted on the main spindle. The starting hole is drilled in this position with the tailstock. For rolling a tool, designed for this use, is fitted to the cross slide. The tool has a roller, which can freely rotate, additionally two sensors for measuring the process forces are integrated. A linear sensor from Burster is used to measure the radial movement. Due to the one-sided bearing of the roller in this setup, the process forces are limited significantly. Additionally, the deflection often leads to an asymmetrical collar. Therefore, a new tool is built [8]. Nevertheless, all tests for the publication at hand were performed with the setup on the conventional lathe.

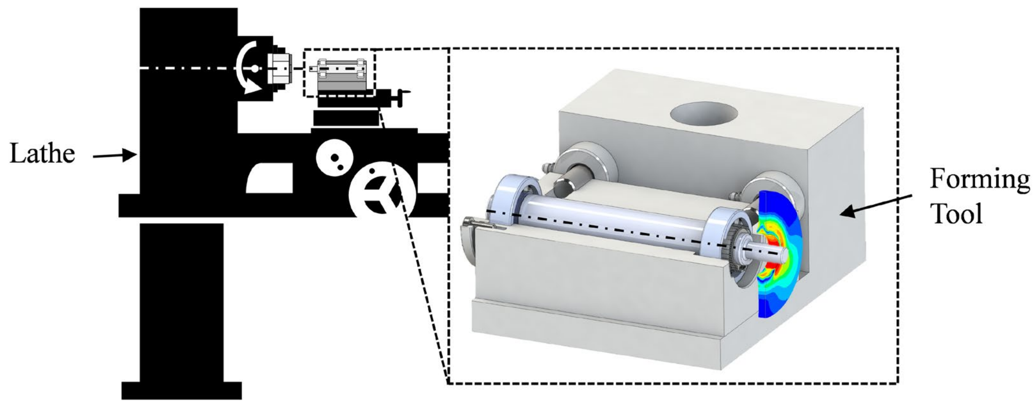


Fig. 2. Punch-hole-rolling setup on a conventional lathe cf. [7].

The final product of punch-hole-rolling is a hole with a collar on both sides of a metal sheet. Pure forming processes which produce similar geometries are collar forming and friction drilling. Compared to these two processes, punch-hole-rolling has three distinct advantages for the use case of forming bearing seats. Punch-hole-rolling produces a double-sided collar; Therefore, the bearing center and the sheet center can be aligned to enhance the force transfer from the bearing to the housing. Additionally, the incremental nature of the process allows for production of the small tolerances required for bearings. Furthermore, the process has multiple degrees of freedom, that can be used to control the material properties.

Characteristic of the Collar Height in Punch-Hole-Rolling

By varying the process parameters in punch-hole-rolling a few different product states can be produced. One of the product properties, that can be influenced is the height of the collar. The height depends strongly on the difference between the initial diameter and the final diameter of the hole in the product, but can be adjusted in a smaller range during the process.

Collar height in DC04.

In [7], tests were performed on DC04 to characterize the forming of the collar and, especially the development of the collar height in more detail. The collar height was found to increase approximately linearly with the change in radius. In [9], it was additionally found that changing the radial feed rate of the process leads to a change in the gradient of the graph. Thereby, a higher feed rate leads to a lower gradient and thus to a lower collar height. Furthermore, it was concluded, that the rotational speed does not influence the collar height in a significant way. In Fig. 3**,** three graphs are shown that highlight the different relations between the collar height and the various process parameters. In each graph, the collar height is plotted over the radius of the hole. The x-axis starts on the starting hole radius, for which 4 mm is chosen in most tests. The y-axis begins at a collar height of 2 mm, which equals the thickness of the sheet metal. Each graph consists of many datapoints, measured on different test pieces, which are hole-rolled to various radii and measured offline. Therefore, steps in the graphs can occur due to variations in the process. On the left side of Fig. 3, the trends of collar height for three different rotational speeds and two different feed rates are depicted. As stated by Mühl et al., the difference in rotational speeds is insignificant compared to the change in feed rate. On the right side of Fig. 3, the trends of collar height for four different feed rates are shown. As can be seen in the first graph, and as stated before, it is clear that the feed rate influences the collar height in a significant way. Nevertheless, the maximum spread of the collar height is quite small with less than 2 mm for a 6 mm widened radius. By changing the starting hole diameter, the collar height can be adjusted in a wider range. For demonstration, a fifth trend is added of test pieces with a starting hole radius of 5 mm. The trend runs parallel to the one with the same feed rate but with a smaller starting hole.

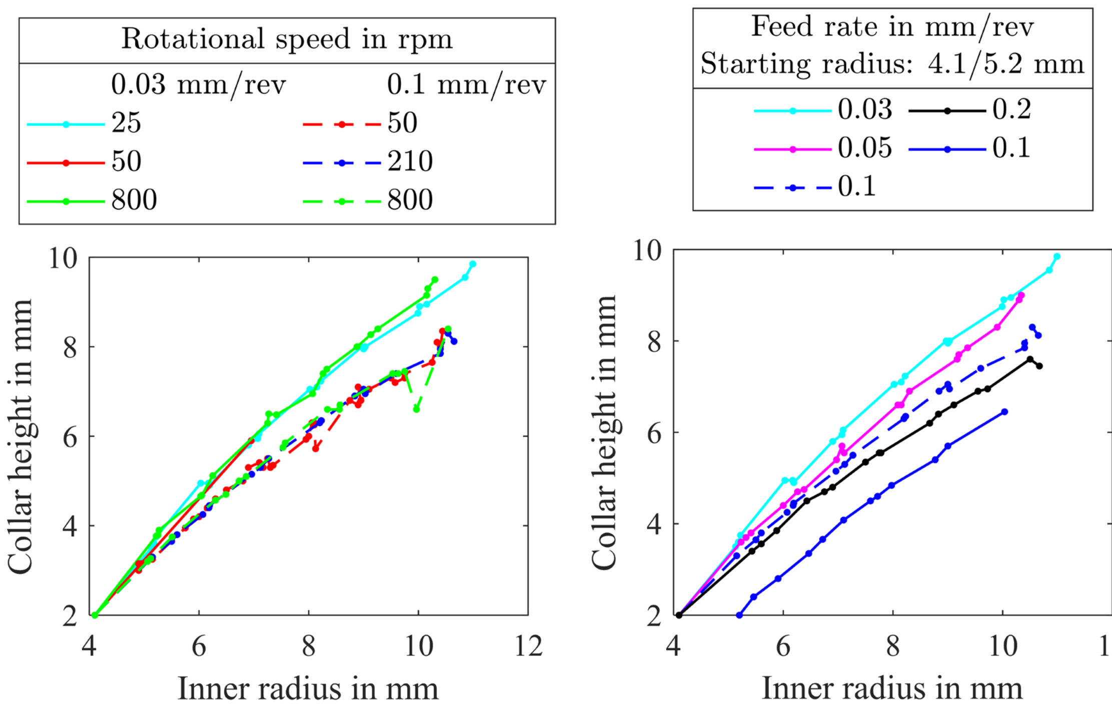


Fig. 3. Trend of the collar height over the inner radius in punch-hole-rolling in the material DC04 for varied process parameters left: for two different feed rates and three different rotational speeds each and right: for four different feed rates at rotational speeds between 25 and 210 rpm and for one varied starting diameter.

Collar height in 1.4301.

To identify the limits of the process and the current test setup, tests were also conducted with the stainless steel 1.4301. This steel has a significantly higher yield stress than the tested DC04. Additionally, this material is affected by the TRIP-effect, which is going to be used in the product property control. TRIP stands for transformation induced plasticity. The effect is the strain induced conversion to martensite. [10] Due to the higher hardness of martensite compared to the normal grain structure of the material, it is possible to change the hardness of the material in dependence of the martensite fraction. The influence of punch-hole-rolling on this product and material property will be discussed in more detail in the following chapter.

To evaluate the correlations between the process parameters and the collar height in 1.4301, the same tests as on DC04 are conducted. It is planned to determine if the same characteristics also can be seen in 1.4301. In Fig. 4, the trend for the collar height in 1.4301 is depicted. Due to the higher strain-hardening coefficient, the process force rises much faster than in DC04. Therefore, it is not possible to reach the same radii with the same force restriction. Additionally, a roller with a bigger diameter has to be used and the feed rate is highly restricted. As seen in Fig. 3, the feed rate has a significant influence on the collar height. Due to the limitations in choosing the process parameters, only a small variation can be achieved. In this case, feed rates of 0.03 mm/rev and 0.05 mm/rev are compared. Nevertheless, a similar trend as in DC04 can be observed. Even though the trend is noticeable, the difference between both parameters is quite small. To rule out measurement noise as a cause, another test is performed with 210 rpm instead of 25 rpm, which is expected not to differ significantly from the test with same feed rate. It can be observed that the trends for the two tests are quite similar and both show a significant difference to the test with the different feed rate. Therefore, it is assumed, that the collar height in 1.4301 has the same characteristics as in DC04. Nevertheless, it is necessary to conduct more tests with the planned, more advanced setup [8].

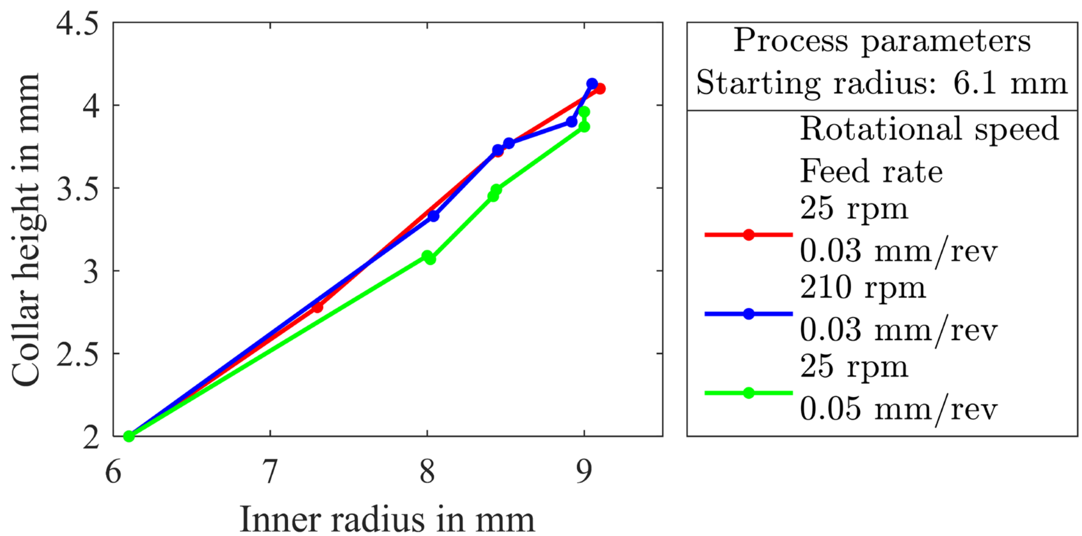


Fig. 4. Trend of the collar height over the inner radius in punch-hole-rolling in the material 1.4301 for varied process parameters.

Characteristic of the Hardness of the Inner Surface in Punch-Hole-Rolling

The second product property, which can be influenced by punch-hole-rolling is a non-geometric one. It is the hardness of the surface on the inside of the formed collar. The hardness is examined for two different materials with different effects for its hardening. The first is DC04, where the hardness increase was discovered and is explained by conventional cold hardening of the material due to the plastic deformation. In 1.4301, the TRIP effect leads to an increase in the martensite fraction and thus to a higher hardness of the material in general. Both characteristics are discussed in more detail in the following chapter.

Hardness in DC04.

In DC04, the hardening of the material due to punch-hole-rolling was measured for the first time. To determine the characteristics more closely in [9] specimens from the previous tests primarily concerning the collar height were examined in more detail. It was discovered that the hardness rises with increasing radius and thus deformation, but remains constant above a certain point. A correlation between the process parameters feed rate and rotational speed and hardness could not be observed. Therefore, the hardness in DC04 cannot be controlled with the punch-hole-rolling process. It is suspected that the increase in hardness occurs due to cold hardening during the deformation of the material.

Hardness in 1.4301.

Due to the disadvantages with DC04, it is decided to use the stainless steel 1.4301 in future tests. As explained before, this steel is affected by the TRIP effect by which the grain structure of the material is transformed into martensite. This effect is strain induced. [10] In preliminary flat crush tests it was shown that the transformation depends on the plastic strain as well as the plastic strain rate. In punch-hole-rolling this leads to a dependence on all of the process parameters. The radial position of the roller in combination with the rotational speed determine the tangential speed between the roller and the material. In Fig. 5 the trend for the surface hardness over the inner radius is shown for two different sets of process parameters. To measure the hardness, the collar was cut and the slice embedded in epoxy. The hardness was measured by conventional means approximately 50 µm below the surface. It can be seen that the hardness generally increases with increasing inner radius and thus plastic strain. Additionally, the trend shows that the increase of hardness is reduced with higher forming rates. This also reflects the behavior observed in the preliminary tests and correlates with the lower measured martensite volume fractions of these samples.

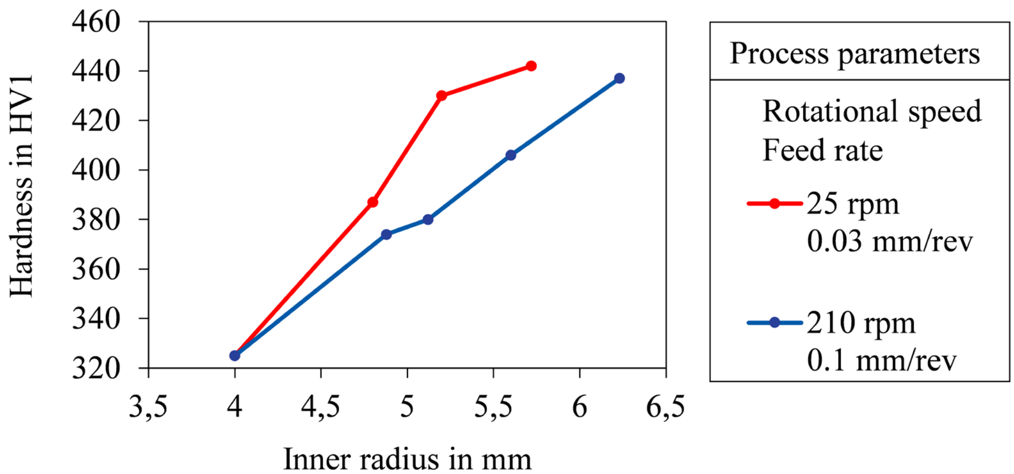


Fig. 5. Trend of surface hardness over the inner radius in punch-hole-rolling in the material 1.4301 for varied process parameters.

Barkhausen noise.

To be able to control the hardness of the material during the process, it is necessary to measure it first. This is especially challenging due to the needed real time capability of this sensor and the necessity to take the measurement without disturbing the forming process. As a suitable solution for this challenge, the Barkhausen noise analysis is identified. This analysis is based on the fact that in ferromagnetic materials the magnetic domains grow during magnetization and therefore the walls between the different domains are moved. Due to interactions of these domain walls with pinning sites such as material defects, sudden changes in the magnetization of the material occur. Measuring the magnetic flux density of the material during a cycle of magnetization and demagnetization results in the so called Barkhausen noise. Due to the interaction of the domain walls with the microstructure of the material the Barkhausen noise includes information about many different material properties. [11-14] In their paper, Mühl et al. showed that the hardness of the material after punch-hole-rolling can be correlated with the root mean square value of the Barkhausen noise signal. [9]. Furthermore Spies et al. have shown in their paper that this is also true for the amplitude of the signal and that it can also be correlated with the alpha martensite volume fraction and the plastic strain in 1.4301. Moreover, a concept was presented for the integration of the sensor into a future test rig. [8] All correlations were identified by taking offline measurements and comparing them with the results of conventional measuring processes [8,9]. Using this data, the online Barkhausen noise measurements can be converted into the product properties of interest. All this taken together shows the theoretical feasibility of a magnetic Barkhausen noise sensor for the use in a process control for punch-hole-rolling.

Proof of the Feasibility of a Multivariable Product Property Control in Punch-Hole-Rolling
The previous chapters have shown, that the collar-height and hardness can be controlled individually in the material 1.4301. This includes proposing Barkhausen noise as a solution to the challenge of inline hardness measurements. The collar-height meanwhile could be measured by a 2D laser scanner. For a multivariable product property control it is nevertheless necessary to prove that this control can also be achieved simultaneously and independently from each other. Since the test setup is currently incapable of proving this experimentally, it is expedient to do so by a theoretical presentation of the proposed closed-loop control strategy instead. Therefore, the process is represented mathematically. In Equation 1 the dependencies of the product properties collar height and surface hardness are depicted. The height of the collar is dependent on the relative radius Δr and the feed rate $\dot{r}$. The starting radius is determined before the process starts, therefore it is not a variable that can be used. The product radius is demanded by the planned application. Therefore, the relative radius is also not variable. By solving the yet to be determined formula for the collar height for the feed rate, it is possible to determine the feed rate, necessary to achieve the desired collar height. The process is quite similar for the hardness, the only difference being that it also depends on the rotational speed. Due to the pre-determined feed rate the formula is solved for the necessary rotational speed.

$$\begin{bmatrix} h_{\mathrm{col}} \\ HV_{\mathrm{sur}} \end{bmatrix} = \begin{bmatrix} f_{\mathrm{hcol}}(\Delta r, \dot{r}) \\ f_{\mathrm{HVsur}}(\Delta r, \dot{r}, \omega) \end{bmatrix} \quad (1)$$

It is obvious that a poorly chosen start radius leads to not achievable numbers in the process parameters. Unachievable product properties will also lead to unrealistic process parameters. Therefore, the set of producible product parameters is finite. In addition, not all combinations of product properties can be reached, even though the properties can be simultaneously controlled in theory. To look into this in more detail, it is suitable to look at the properties that can be achieved with the given range for the forming parameters. Since the process varies a lot for different roller diameters and relative radii these will be defined for this example. The following numbers are valid for a roller diameter of 8 mm and a relative radius of 2 mm. The feed per revolution can be varied between 0.03 mm/rev and 2 mm/rev whilst the rotational speed can be varied between 25 rpm and 800 rpm. In Fig. 6, an approximation of the working area for this parameter set is shown. It should be noted that some of the depicted values are approximated an may change slightly with further research. Nevertheless, the diagram is suitable to get a quick overview. In the corners the extreme values of the possible parameter combinations are shown. The first number describes the rotational speed and the second one the feed per revolution. It can be noted that in the lower left corner two points correspond to another. This happens because the feed per revolution of 2 mm/rev is so high that no transformation to martensite is expected to occur even at the lowest rpm. The hardness of 300 HV1 matches the hardness of the base material. Due to cold hardening, this is nevertheless likely to increase to a limited extent.

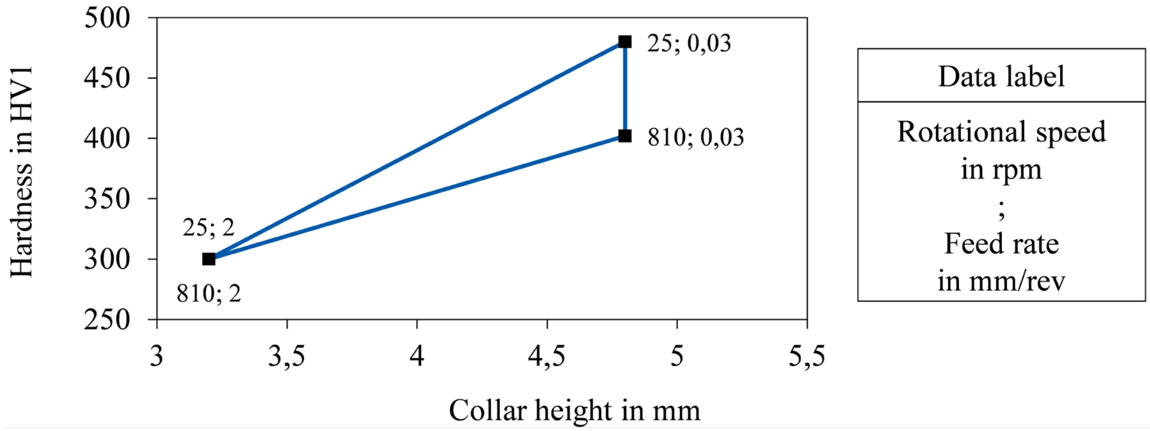


Fig. 6. Approximation of the achievable product properties, collar height and surface hardness for a given set of process parameters in the material 1.4301.

Concept for a Multivariable Product Property Control in Punch-Hole-Rolling

In order to control the process, the transfer behavior of the manipulated variables $\boldsymbol{u} = [\dot{r} \quad \omega]^T$ to the product properties to be controlled $\boldsymbol{x} = [h_{\text{col}} \quad HV_{\text{sur}}]^T$ is of essential importance. The relations described in Eq. 1 can be described using data-driven models of varying complexity. In this context, data-driven models have two elementary advantages. First, the complex relationships between manipulated and controlled variables do not need to be described by analytical models. Second, large parts of data-driven models are differentiable, which is especially useful for control engineering applications. If the functions f_{hcol} and f_{HVsur} presented in equation 1 are fitted via data-driven models and then derived with respect to the manipulated variables, formulas for the rates of change of the variables according to Eq. 2 follow.

$$\dot{\boldsymbol{x}} = \frac{\partial [f_{\text{hcol}}(\boldsymbol{u}) \quad f_{\text{HVsur}}(\boldsymbol{u})]}{\partial \boldsymbol{u}} \cdot \dot{\boldsymbol{u}} = \boldsymbol{J}(\boldsymbol{u}) \cdot \dot{\boldsymbol{u}} \tag{2}$$

The locally linearized inverse of the Jacobian matrix $\boldsymbol{J}(\boldsymbol{u})^{-1}$ can now be used to transform deviating-controlled variables $\boldsymbol{e}_x$ into velocity changes of the manipulated variables $\Delta\boldsymbol{u}$. Fig. **7** provides an overview of the proposed closed-loop control approach. The reference variable for the properties to be controlled is a time series whose final values are the final collar height and hardness. Deviations between the desired time series $\boldsymbol{x}_{\text{des},t-1}$ and observed time series $\hat{\boldsymbol{x}}_{\text{act},t-1}$ can be transformed into velocity changes of the manipulated variables $\Delta\boldsymbol{u}$ via the inverse Jacobian matrix $\boldsymbol{J}(\boldsymbol{u})^{-1}$ and carefully selected gain factors $k_{\text{P},i}$ in the diagonal gain matrix $\boldsymbol{K}_{\text{P}}$. The elements of the diagonal gain matrix thus weight the control deviations of the corresponding control variables x_i and lead to low control dynamics if chosen too low or to oscillations if chosen too high. These calculated velocity changes $\Delta\boldsymbol{u}$ can then be added to the manipulated variable $\boldsymbol{u}_{t-1}$ generated in the last cycle step of the control unit and lead to the manipulated variable $\boldsymbol{u}_t = \boldsymbol{u}_{t-1} + \Delta\boldsymbol{u}$ of the next cycle. In the punch hole rolling process, the implemented sensors are then used as input variables for an observer $\boldsymbol{f}_{\text{obs}}$ that observes the product properties $\hat{\boldsymbol{x}}_{\text{act}}$ from the sensor signals $\boldsymbol{s}$. In the observer, the correlations between recorded sensor signals and the controlled variables that have already been investigated in published papers (e.g. magnetic Barkhausen noise and hardness) are used to estimate the actual states of the controlled variables. [8, 9] These are then in turn used in the feedback loop of the control scheme to determine the control deviation.

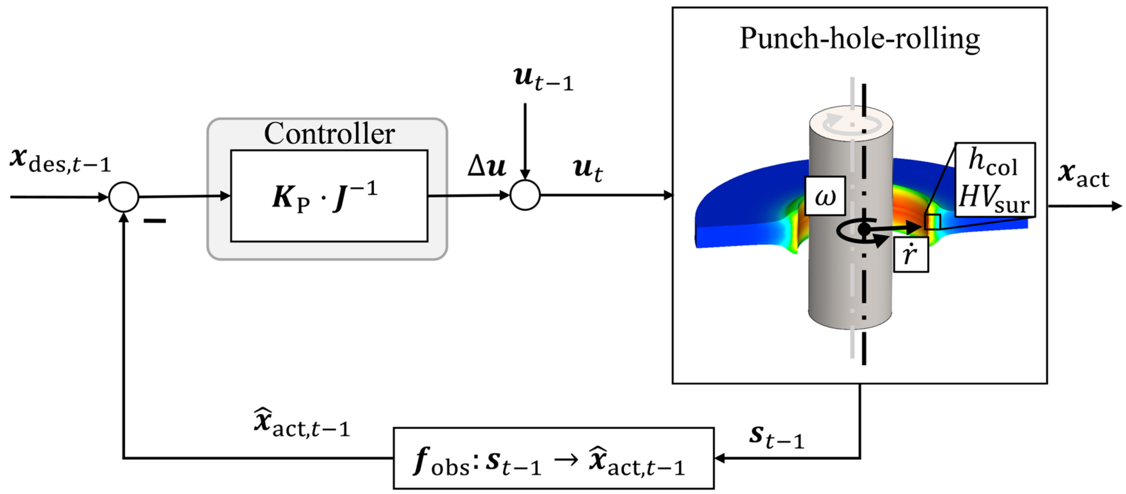


Fig. 7. Block Diagram of the proposed closed-loop control approach for punch-hole-rolling.

Summary

In this paper, the basic behavior of the material, formed by punch holing was presented. In particular, the changes of the product properties of interest, collar height and surface hardness on the inside of the collar during the process have been discussed. Subsequently, the possibility for a multivariable product property control in the punch-hole-rolling process was shown, supported by the data presented prior. Lastly, a concept for the control itself was established, considering the difficulty of controlling more than one property at a time, which are not completely independent of each other. It is planned to validate the theoretical possibility for the multivariable product property control presented in this paper in the near future by means of further tests. The upgraded test setup required for this is being built currently. It is also planned to implement the concept for the control scheme shown in the new test setup and to test and improve its suitability as well.

Acknowledgement

The authors would like to thank the German Research Foundation DFG for the support of the depicted research within the priority program ‘SPP2183’ through project no. ‘424334856‘.

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