An inverse approach for the geometry prediction of sheet-metal parts with embossings made of high- and ultra-high strength steels

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Abstract. Embossing or offsetting is a shear forming process closely related to fineblanking. It is mainly used for the manufacturing of functional geometry features like alignment pins on brake calipers or gears of seat adjustments. To achieve weight reduction, a trend towards the usage of high- and ultra-high-strength steels can be observed. Especially in embossing, the lack of knowledge for these grades evokes challenges in part design due to the higher springback and the different forming behaviour which greatly influence the characteristics of the formed geometry. Furthermore, Finite-Element simulations for geometry prediction are not yet able to achieve satisfying results due to the challenging material testing of the sheet-metal material. To address this problem, a novel method for the geometry prediction of sheet-metal parts with embossings made of high- and ultra-high-strength steels is proposed and demonstrated on the mild steels HSM 355 and HLB 22 as well as the high-strength steels HSM 700 HD and StrenX 700 MC plus. The method is based on the experimental identification of simple embossing geometries. Especially the die-roll was in the focus of interest, as it reduces the area available for functional features. A routine for the determination of the die-roll using the second derivative of the surface profile was implemented. The material model is subsequently calculated by an inverse algorithm. Furthermore, the dependency between the part’s geometry and the flow curve was investigated to reduce the calculation time. It is shown, that it is possible to determine a material model, which is capable of predicting the geometry of a part with an embossing for different materials and process parameters.

1. Introduction

According to DIN 8580 [1] and DIN 8587 [2] embossing is part of the shear forming processes. The literature is not consistent on the name of this process. While Schmidt et al. [3] refer to it as embossing, it is called offsetting in DIN 29548 [4] and, especially for applications where the punch is significantly
bigger than the die, sheet metal extrusion process e.g. in [5]. A basic setup with all parts directly involved in the forming process as well as the characteristics of the formed surface are presented in Figure 1.

![Diagram](image-url)

**Figure 1.** Schematic setup for embossing with the punch force $F_S$, the blank holder force $F_{NH}$ and the counter punch force $F_{GH}$ (a) and characteristics of the formed surface (b) according to [3], [6] and [7].

It can be observed, as stated in [6], that the embossing process is closely related to the fineblanking process with regards to tool technology, the used materials and the process parameters.

A typical part with embossings shows a considerable die-roll, which depends on several factors like the geometry, the material, the edge condition of the active elements (especially punch and die edge radii $r_S$ and $r_M$ in Figure 1) and the die-clearance [8]. Usually, a small die-roll is desirable due to the bigger surface available and therefore a lower surface pressure e.g. in embossed gears. The die-clearance $u$ is the most important process parameter for manufacturing parts without cracks. As in blanking, this parameter can be positive (punch smaller than die), zero or negative (punch bigger than die) [9]. The effects of different die-clearances on the maximum embossing depth and wear of the active elements have been investigated in [6] and [10]. It was found that a negative die-clearance prevents cracks even at high embossing depths.

A combination of the fineblanking and the embossing process was the focus of the work of Zheng et al. [11]. The enhanced assumed strain Finite-Element method to analyze the process was introduced by Cheng et al. [12]. The material flow behavior for different punch and die radii was investigated by Suriyapha et al. [13]. This was extended by Zhuang et al. for different die-clearances with or without an additional hole in the center of the specimen. Here, the material model was identified by comparing the results of different extrapolation models calibrated by a tensile test with a torsion test. This is already close to an inverse parameter identification, but there is no systematic approach known to the authors for the embossing process. Nevertheless, the feasibility has been proven for the fracture criteria parameter identification in blanking by Hambli and Reszka [14]. This knowledge gap will be addressed in this work, especially for the prediction of the die-roll height.

2. Material characterization and modelling

For the experiments, four different sheet metal materials have been used, each with a thickness of 4 mm. The first, HSM 355 (S355MC, material number 1.0976) is a microalloyed finegrain structural steel, typically used for fineblanking [15]. It is standardized in DIN EN ISO 10149-2 [16]. The second, HLB 22 (also 22MnB5, material number 1.5528) is a boron alloyed heat-treatable steel. Due to its good formability and the high strength after quenching, it is commonly used for vehicle parts with high safety requirements [17]. The third, HSM 700 HD (S700MC, material number 1.8974), is a microalloyed finegrain structural steel with a high ductility and a higher yield strength compared to HSM 355 [18]. The last, StrenX 700 MC plus is an advanced high strength steel which exceeds the requirements for an S700MC [19].
2.1. Chemical characterization
The chemical composition of the test materials was investigated to ensure the transferability of the experimental results. This was carried out with the optical emission spectrometer “Foundry Master” by the company Oxford Instruments plc, Abingdon (United Kingdom). As presented in Table 1, all the alloying elements are within the ranges specified by the manufacturers.

Table 1. Chemical Composition of the test materials in percentage by mass.

| Alloying Element | C     | Si    | Mn    | P    | S    | Al    | Cr    | B    | Nb   | V    | Ti    | Mo    |
|------------------|-------|-------|-------|------|------|-------|-------|------|------|------|------|-------|
| HSM 355          | 0.020 | 0.010 | 0.163 | 0.009| <0.002| 0.024 | 0.069 | <0.001| 0.024| <0.002| <0.001| <0.006|
| HLB 22           | 0.205 | 0.230 | 1.260 | 0.012| <0.002| 0.038 | 0.150 | 0.001| <0.005| 0.005| 0.042 | <0.005|
| HSM 700 HD       | 0.041 | 0.060 | 1.630 | 0.013| <0.002| 0.036 | 0.054 | <0.001| 0.033| 0.009| 0.112 | 0.159 |
| StrenX 700 MC plus| 0.048 | 0.060 | 1.842 | 0.007| <0.002| 0.026 | 0.061 | <0.001| 0.044| 0.047| 0.111 | <0.006|

2.2. Mechanical characterization
To identify the mechanical properties of the materials, tensile tests according to DIN 6892 [20] have been carried out on the tensile testing machine 1484/DUPS-M by the company Zwick GmbH & Co. KG, Ulm (Germany). The specimen geometry E 4 x 10 x 35, as specified in DIN 50125 [21], was chosen. The tests were performed on ten specimen taken out of the sheet metal in 0°, 45° and 90° to the rolling direction. The results of the tensile tests are presented in Table 2.

Table 2. Yield and tensile strength of the investigated materials for different angles to the rolling direction (RD).

| Angle to RD | 0° | 45° | 90° | 0° | 45° | 90° |
|-------------|----|-----|-----|----|-----|-----|
| HSM 355     | 379| 398 | 402 | 449| 452 | 458 |
| HLB 22      | 366| 362 | 374 | 499| 496 | 509 |
| HSM 700 HD  | 756| 760 | 836 | 858| 825 | 881 |
| StrenX 700 MC plus | 737| 748 | 804 | 823| 817 | 875 |

According to the steel manufacturer, the reason for the lower tensile stress in the 45° direction is caused by the rolling process combined with the fact that the specimens were not cut out at the exact centre of the sheet to save material.

2.3. Material modelling
The extrapolation formulas attributed to Voce and Swift were chosen for the material modelling. While the first usually underestimates hardening, the second overestimates it. To be able to adjust the material model in the optimization process, a large range of different material behaviours, going from close to ideal plastic up to a distinct hardening is desirable. This is achieved by extrapolating the lowest flow curve for a given material by the Voce formula (1) while extrapolating the highest one with the Swift formula (2). Both are listed below along with a formula (3) which allows to interpolate between the two models.

\[ k_{fV} = k_{f0} + A_V \left(1 - \exp \left(\frac{\varphi}{B_V}\right) \right) \]  
(1)

\[ k_{fS} = A_S (B_S + \varphi)^n \]  
(2)

\[ k_f = a k_{fV} + (1 - a) k_{fS} \]  
(3)
3. Experimental setup

3.1. Embossing tool
The used embossing tool shows a massive, overdimensioned construction to minimize the influence of bending. To ensure a high accuracy, four guiding pillars with precision roller cages were used. Six piezoelectric load cells allow to monitor the process forces during the process while the punch and blank holder movements can be tracked by two inductive displacement sensors. The tool is displayed in Figure 2 a).

3.2. Fineblanking press
The triple action fineblanking-press HFA 3200 plus by the company Feintool, Lyss (Switzerland), was used for the experiments. The high nominal pressing force of 3200 kN together with small guiding tolerances reduce the influence of the press on the measured results. The press is displayed, together with the tool in Figure 2 b).

![Figure 2. The embossing tool (a) and the Fineblanking press Feintool HFA 3200 plus (b).](image)

3.3. Tactile surface measurements
The tactile surface measurements were carried out on the surface measuring station MarSurf PCV with a PCV 200 drive unit by the company Mahr GmbH, Göttingen (Germany). This device has a resolution of 0.5 µm for a measuring arm length of 350 mm and thus guarantees highly accurate results. Ten specimens were measured on the surface orientated towards the punch for each material and embossing depth.

3.4. Process parameters and results
The punch was designed with a diameter of 15 mm. To reduce the risk of fracture, a negative die-clearance of -25 µm was chosen together with chamfers on punch and die. The chamfer of the punch was 0.3 mm high while the one on the die was 1 mm high. Both showed an angle of 30° to the axis of symmetry. The cutting edge radii (r_s and r_m in Figure 1) were polished to 50 µm. Furthermore, the active elements were coated with FeinAl to reduce wear. To ensure a low friction, the sheet metal was oiled with Fuchs Wisura 3180. A embossing speed of 50 mm/s, a common speed in industrial applications, was set. Each material was tested with two different embossing depths of 70 % and 90 % (i.e. 2.8 mm and 3.6 mm) of the sheet metal thickness. The results are presented in Figure 3.
4. Finite-Element simulations

4.1. Simulation model
The Finite-Element simulations were performed with Abaqus 6.12-3, by the company Simulia, Johnston (United States). This tool was chosen due to its open interface, which makes it easy to integrate the optimization algorithm via Python™. The setup was assumed to be axisymmetric with a fixed die and a moving punch. Linear elasticity was considered in both active elements. Blank holder and counter punch were modelled as rigid bodies, each subjected with the same force as in the experiments. To reduce mesh distortions, the ALE-formulation was used. The model is displayed in Figure 4.

4.2. Inverse parameter identification routine

4.2.1. Determination of the die-roll
To automatically evaluate a surface profile (Figure 5 a), an algorithm for the detection of the die-roll is necessary. The transition of the sheet metals upper surface to the formed surface usually shows a sharp edge. Therefore, the second derivative of the surface profile is used for the determination of the die-roll. First the surface profile is rotated by 45° to achieve a well-defined function for the whole surface profile (Figure 5 b). Afterwards, the derivatives are calculated and the minimum is searched. This procedure is illustrated in Figure 5 c). Afterwards, an error estimation has to be carried out. Due to the linear approximation of the FEM-mesh, the real die-roll is somewhere on the surface profile either on the element above or below the point of the lowest second derivative. Therefore, the error is equal to the height of one of those elements. To get a reasonable estimation, the mean of those heights is considered as the error.
4.2.2. Dependency between die-roll and material model

To reduce the effort for the inverse parameter identification, it is advantageous to know the dependency between die-roll and material model. Therefore, a series of simulations has been performed for the material HLB 22 and different combinations of $k_R$ and $k_{RV}$. This showed an almost linear dependency between the die-roll and the interpolation factor $\alpha$, which is displayed together with the extrapolated flow curves in Figure 6.

4.2.3. Algorithm for the parameter identification

At first, two initial simulations are computed to get results for $\alpha = 0$ and $\alpha = 1$. Afterwards, the die-roll height is determined by the algorithm presented above. The deviation between the die-roll height of the experiment and the simulations are computed. If none of these results is not within the range determined by the error estimation, a new starting point has to be set. This is carried out by a linear interpolation between the simulation results and calculating for which $\alpha$ the deviation is zero. A new material model is generated with this $\alpha$, inserted in the simulation model and computed. Afterwards, the same procedure as explained above is carried out again, with the only difference that the nearest two points in the $\alpha$ - $h_k$ diagram are chosen for the interpolation. If the result is within the tolerance, the optimization is finished and $\alpha$ is displayed.
5. Comparison between experiments and simulation

The experimentally determined die-roll heights are presented together with the results of the optimization routine in Figure 7.

Figure 7. Comparison between experiments and simulations for the tested materials and the two embossing depths.

Regarding the experiments, it can be observed, that the embossing depth has almost no influence on the die-roll height. The biggest difference between \( h_D = 70\% \) and \( h_D = 90\% \) is 6 µm (0.15 % of \( t \)) for StrenX 700 MC plus. This can be attributed to the fact that the die-roll’s formation occurs very early during the process and is already finished at the high investigated embossing depths. On the other hand, the influence of the material on the die-roll height is significant. The difference between HLB 22, the highest observed, and StrenX 700 MC plus, the lowest of all, is 65 µm (1.6 % of \( t \)). The materials with a low yield strength and high strain hardening show a higher die-roll than the high-strength steels. Nevertheless, the optimization routine was able to achieve very accurate results for all the materials.

6. Conclusion

The aim of this paper was to identify a material model, which is capable of predicting the die-roll height of sheet metals with embossing made out of high- and ultra-high strength steels. This was achieved by experimentally determining the die-roll height for four different steels while varying the embossing depth. By carrying out a chemical composition analysis and tensile tests, the standardized properties of the steels were verified. The thus determined flow curves were used to calibrate the material models attributed to Swift and Voce. Afterwards the Finite-Element simulation model was presented. Based on the computed results, an algorithm for the detection of the die-roll was explained, which is based on the calculation of the second derivative. Several results were calculated for the steel HLB 22. An almost linear dependency between the die-roll height and the interpolation factor between the Swift and Voce material models was observed. This indicates, that the formation of the die-roll is strongly correlated to the strain hardening of the material. Afterwards, this was used for the optimization algorithm. Here, two simulations were carried out at first to identify the boundaries for the inverse analysis. Subsequently, the deviation between the die-roll height in experiment and simulation is minimized by interpolating between those results and thus calculating a new starting point for the next iteration step. When the result is within a tolerance, which depends on the mesh size, the optimization stops and the computed material model is saved. By the comparison of experiment and simulation, it was found that very accurate predictions of the die-roll heights are possible for the four steels.

The routine can be used to save testing time, as only the flow curves of the investigated material and a simple embossing experiments are needed. This method could be extended by the identification of temperature and strain-rate dependency as well as to find a suitable damage model. Thus, the big limitations in embossing simulation, the missing material properties at high strains, strain-rates and temperatures can be overcome.
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