Modeling of Cylindrical Flow Forming Processes with Numerical and Elementary Methods

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In flow forming – an incremental forming process – the final geometry of a component is achieved by a multitude of minor sequential forming steps. Due to this incremental characteristic associated with the variable application of the tools and kinematic shape forming, it is mainly suitable for small and medium quantities. For the extensive use of the process it is necessary to have appropriate simulation tools. While the Finite-Element-Analysis (FEA) is an acknowledged simulation tool for the modeling and optimization of forming technology, the use of FEA for the incremental forming processes is associated with very long computation times. For this reason a simulation method called FloSim, based on the upper bound method, was developed for cylindrical flow forming processes at the Chair of Virtual Production Engineering, which allows the simulation of the process within a few minutes. This method was improved by the work presented with the possibility of geometry computation during the process.

Keywords: Elementary Methods, Flow Forming, Finite-Element-Method (FEM)

Introduction

Incremental forming processes are one of the oldest manufacturing methods in the world. Flow forming is an incremental forming process that is established e.g. for the production of high quality gear parts. Due to this incremental character, associated with the variable application of the tools and the kinematic shape forming, it is mainly suitable for small and medium quantities. It is not necessary to produce special tools for every single workpiece.

The principles of the two process variants which are used in the production of cylindrical parts are shown in Fig. 1. The material that is displaced between the roller and the mandrel predominantly flows in the axial direction and therefore causes an elongation of the workpiece. In their final shape the parts have an increased strength and a better surface quality [1]. Overall flow forming fulfills high quality requirements, and by the partial opportunity to eliminate complete pass it is possible to reduce the manufacturing costs by up to 50% [2].

Research activities for the theoretical investigation and description of the process have been undertaken for decades. So, experimental investigation methods are currently sufficiently advanced to determine difficult measurable factors like plastic strain [3, 4, 5]. These experimental investigations are often realized in combination with the Finite-Element-Method (FEM), because FEM is the best tool for the determination of hard measurable or non-measurable results.

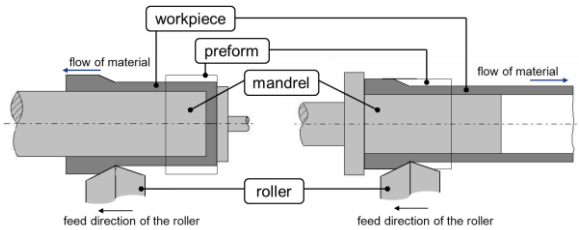

Figure 1 Flow forming principles for cylindrical components

By the incremental forming processes, like flow forming, FEM has the disadvantage of very long computation times. To reduce the computation time, different approaches were developed, e.g. in the SPP1146 “Modeling incremental forming processes”. In particular, for the flow forming of cylindrical components, the model “ModIni” was developed, which enables the quasi-stationary stage of the process to be accomplished faster using a modified initial geometry. So it was possible to reduce computation time by about 30% [6].

For realizing acceptable computation times, completely new approaches like the “Shape

Deformation Model Method (FMM)" were also developed [7]. But this method partially works with approximated or rough values, because some necessary process parameters for the validation are not measureable.

However, the most frequently used basis for the theoretical description and development of approaches for modeling the process are the different approaches of the plasticity theory, like the upper bound method [8, 9].

Based on this approach the simulation method FloSim was developed [10]. The FloSim method will be improved by the following specified approach for the calculation of the material flow based on volume consistency.

FEM Simulation

For the circumstantial investigation of the process and to generate reference values, FEM simulations are realized during the presented works. Therefore the simulation software simufact.formingGP version 9.0 from simufact.engineering GmbH was used. This software features a special meshing method for ring-shaped parts, called "RingMesher", that allows a considerable saving in computation time.

The general configuration of the simulation model equates to the principle of three-roller backward flow forming (Fig. 2). Rollers and mandrel are rigid tools described by analytical surfaces. In addition, the fixing of the workpiece in the chuck, in the axial direction, was realized with an analytical surface. This restricts the material flow of the workpiece in the axial feed direction (X), so that the material only can flow contrary to the feed direction.

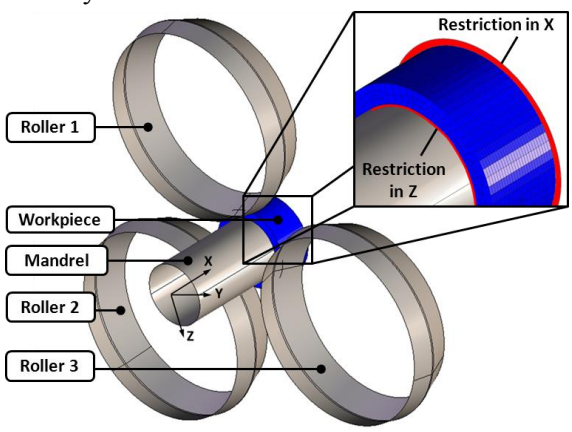

Figure 2 Design of the simulation model

To calibrate the simulation model a preliminarily experiment was simulated, with the parameters shown in Tab. 1.

Table1 Dimensions of Tools and Process Parameters

Parameter	Value
Inner Diameter [mm]	44
Wall thickness s_0 [mm]	4
Roller Diameter [mm]	140
Attack Angle α [°]	22
Feed Rate f [mm/rev]	0.2
Reduction R [%]	40
Speed of Rotation [rpm]	400

The simulation results for this reference process are in very good accord with reality. A comparison between the simulated and experimental normal forces is shown in Fig. 3.

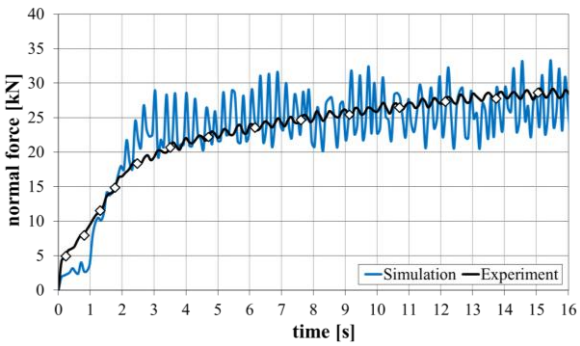

Figure 3 Experimental and simulated normal forces

The computed geometry of the forming zone (Fig. 4) also shows very good accordance with the real workpiece. In particular, the accuracy of the pile-up, on the outside of the part, has to be distinguished. The small bulge ($s_w = 0.2$ mm) under the forming zone alone, on the inside of the workpiece, cannot be exactly represented by the simulation model shown. To represent the bulge more precisely, this area of the forming zone has to be meshed in more detail around the whole periphery, but this would lead to significantly higher computation times. However, the bulging is generally marginal, so it is not very important for the aimed approach, the computation of the workpiece length. Hence, the deviation of the simulation model in that respect was neglected.

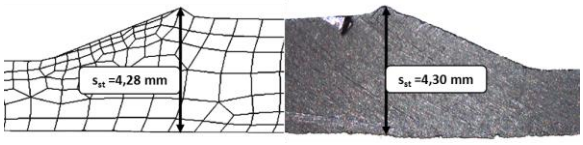

Figure 4 Simulated and experimental geometry of the forming zone

Therefore, it can be noted that it is possible to represent the process close to reality, with the simulation model shown. Thus the realized simulations can be used as a basis for comparison, for the aimed approach, for the optimization of the FloSim simulation method.

The FloSim Model

The FloSim model is a method based on the upper bound method, for the computation of the strain, power and forces of cylindrical flow forming processes [10]. Based on defined velocity fields, the total power P_{ges} is made up of the deformation power P_U, the friction power P_R and the shear power P_S. The deformation power results from the deformation of a volume element between two roller contacts.

$$P_U = \int_V k_f \sqrt{\tfrac{2}{3}\dot{\varphi}_{ij}\dot{\varphi}_{ij}}\, dV = \int_V k_f \dot{\varphi}_v dV \qquad (1)$$

k_f is the yield stress and $\dot{\varphi}_v$ is the equivalent strain rate. The friction power is computed with

$$P_R = \int_{A_R} |\Delta v| \tau_R dA_R \ . \qquad (2)$$

Thereby Δv is the velocity difference in the contact area caused by the deformation of a volume element and the slippage between the workpiece and roller. A_R describes the friction area and τ_R the frictional shear stress.

By the partition of the forming zone into volume elements, a different velocity field is established for each volume element. The power resulting from the different velocity fields is computed with

$$P_S = \int_{A_S} |\Delta v| \tau_{\max} dA_S \ . \qquad (3)$$

Here Δv is the velocity difference between the volume elements and τ_{max} is the maximum transferable shear stress of the material.

The total power of the process is computed with

$$P_{ges} = P_U + P_R + P_S \ . \qquad (4)$$

From this the total force is determined with

$$F = \frac{P_{ges}}{v_0} \ . \qquad (5)$$

Thereby v_0 represents the radial velocity of the roller.

The hardening of the material occurring during the process is considered over the yield stress k_f. For the description of the yield stress the approaches from *Ludwik* [11]

$$k_f(\varphi_v) = C \cdot \varphi_v^n \qquad (6)$$

and from *Spittel* [12]

$$k_f = K_S \cdot e^{(m1 \cdot T)} \cdot \varphi^{m2} \cdot \dot{\varphi}^{m3} \cdot e^{m4/\varphi} \qquad (7)$$

are integrated into the model.

The method described was implemented in Java-based software FloSim, and thus allows the fast computation of local and global process values for the flow forming of cylindrical components.

However, the pile-up ahead of the roller, is so far neglected in the model. Until now it has not been possible to compute and visualize the workpiece length during the process.

Computation of the workpiece length

The easiest way for the computation of the current workpiece length, i.e. of the material flow, is based on the volume consistency. The volume that is displaced during every deformation step cannot be lost; it causes a change in geometry of the component in the radial and longitudinal directions. According to *Hayama*, this volume can be subdivided into a pile-up volume, which flows continuously ahead of the roller in the feed direction, and in that volume that causes the lengthening of the part in the axial direction [13]. On the basis of different experimental and simulation investigations, it is expected that the complete pile-up is not reached until full roller contact. Due to the continuous

existence of the pile-up ahead of the roller, the pile-up volume does not cause any lengthening of the workpiece. That is, by reaching full roller contact, the pile-up volume only has to be deducted once from the volume formed. Also *Hayama* explained that the tilt angle, at the end of the pile-up, had no significant effect, and defined it equal to the roller attack angle α. With this assumption the pile-up volume can be computed with

$$V_{pile\text{-}up} = b_d \cdot \left(\frac{(s_{st} - s_0)^2}{\cos\alpha} \right). \qquad (8)$$

Therefore the required pile-up height s_{st}, for the material, 42CrMo4, used in the reference test, can be computed with the following equation (Eq. 9) [6].

$$s_{st} = 1{,}196 \sin\alpha + 0{,}849 s_0 + 0{,}007 R + 0{,}99 f \qquad (9)$$

The volume formed per deformation step V_{formed}, which causes the lengthening of the workpiece, is made up of the formed cross-section plane A_{formed}, the formed width b_d, the number of rollers i_R, the rotation speed of the workpiece n, the time step size Δt and the current perimeter of the workpiece U.

$$V_{formed} = A_{formed} \cdot b_d \cdot i_R \cdot (n \cdot \Delta t) \cdot \left(\frac{U}{b_d} \right) \qquad (10)$$

The formed cross-section plane A_{formed} has to be computed depending on the roller contact (Fig. 5, Fig. 6). For the startup phase of the process, where the full roller contact is not reached, it is

$$A_{formed} = s_{vr} \cdot l_{d(i-1)} \cdot \sin\alpha + \tfrac{1}{2} s_{vr} \cdot \tan\alpha \,. \qquad (11)$$

Thereby A_{formed} is computed on the basis of a triangle and a parallelogram (Fig. 5), which are described by the formed length l_d, the feed relating to the rollers s_{vr} and the roller attack angle α.

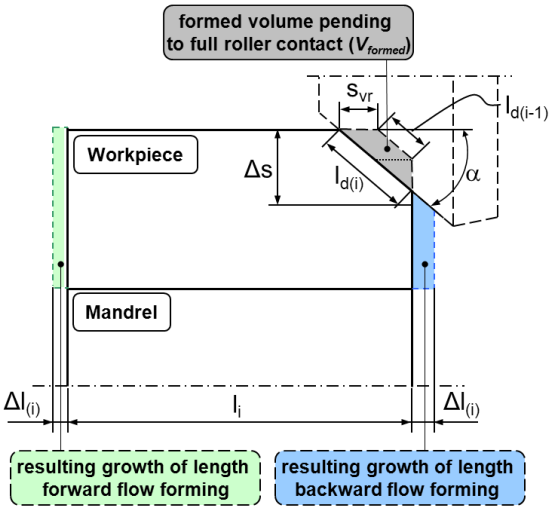

Figure 5 Calculation of the length during the start-up phase

When the roller is in full contact (Fig. 6) with the workpiece, i.e. the final diameter is reached, A_{formed} is computed with

$$A_{formed} = s_{vr} \cdot l_d \cdot \sin\alpha = s_{vr} \cdot \Delta s_{ges} \qquad (12)$$

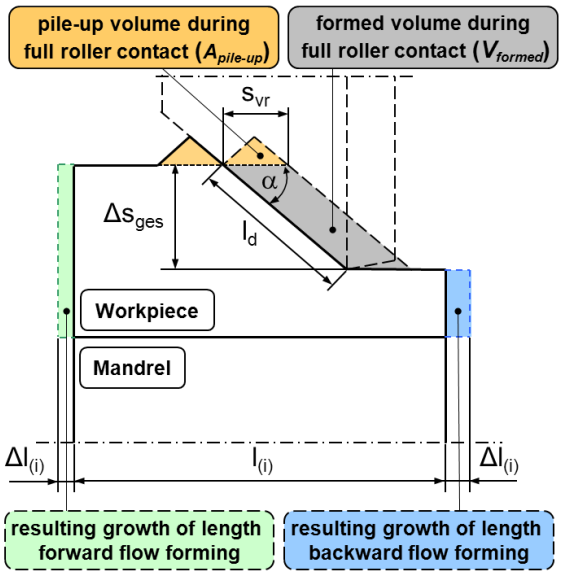

Figure 6 Calculation of the length during full roller contact

Based on the formed volume it is now possible to compute the resulting change in length $\Delta l_{(i)}$ of the workpiece. This is realized depending on the process variant. For forward flow forming use

$$\Delta l_i = \frac{V_{formed}}{\pi \cdot (R_a^2 - R_i^2)} \tag{13}$$

and for backward flow forming use

$$\Delta l_i = \frac{V_{formed}}{\pi \cdot (R_{ews}^2 - R_i^2)} \tag{14}$$

In which R_i is the inner diameter, R_a the initial outer diameter and R_{ews} the current outer diameter of the workpiece. As previously described, the pile-up volume only has to be deducted once from the resulting change in length, by reaching full roller contact.

Results

The presented approach was integrated in the FloSim simulation method, which was developed at the Chair of Virtual Production Engineering. For this the input menu, with additional input parameters, as well as the output menu, with a visualization of the workpiece in 2D, are extended (Fig. 7). For the computation of A_{formed} it is necessary to consider if the roller is already in full contact with the workpiece or not. This is realized within the program on the basis of the current reduction in wall thickness.

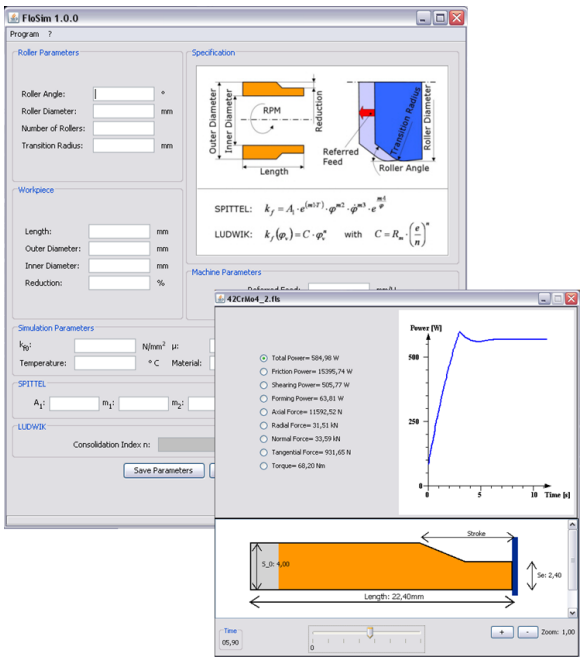

Figure 7 Calculation of the length during full roller contact

A comparison between the computed trend of the workpiece length over the forming process using FloSim and FEM is shown in Fig. 8 and Fig. 9 for both process variants. The values for forward and backward flow forming are in a good accordance. Thus, the presented approach is as comparably well suited for the computation of the workpiece length of cylindrical flow forming parts as FEM. Therefore the approach is an important improvement to the FloSim method.

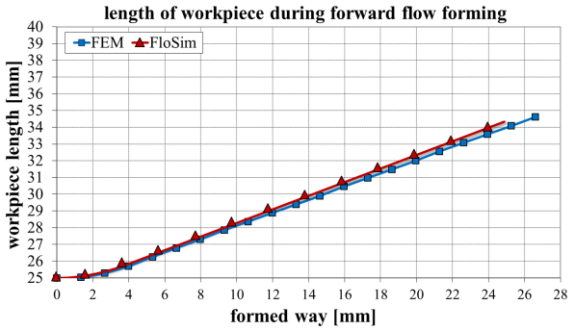

Figure 8 Comparison of the calculated length for forward flow forming

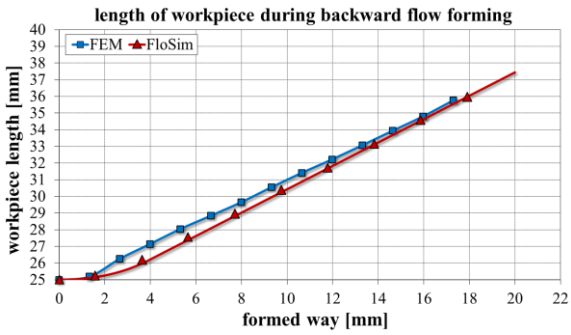

Figure 9 Comparison of the calculated length for backward flow forming

Conclusion

By experimental investigation and FEM simulations based on the experiments, a basis for comparison for the change in length of the workpiece during the forming process was developed. Furthermore, based on these works the geometrical formation of the forming zone during the flow forming process could be better analyzed. In association with the existing approach for the computation of the pile-up height [6] it was possible to integrate the formation of the pile-up in the developed approach for the computation of the length of the workpiece.

The possibility of the computation and

visualization of the workpiece length constitutes an important improvement to the FloSim simulation method.

Through the integration of the pile-up in the simulation method it is furthermore possible to consider the shape of the real contact area, for the computation of the necessary power and force. For further optimization, the aim of future research work is the development of an approach for the material-independent computation of the geometry of the pile-up and bulge parameters.

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References

[1] P. Groche, M. Türk, O. Görtan, H.W. Raedt: *Aktuelle Entwicklungen in der inkrementellen Massivumformung*, Schmiede-Journal, March 2011, pp. 28-30

[2] A. Lentner: *Drückwalzen-Getriebeteile und Räder rationell herstellen*, Industrieanzeiger, 4, 2000, pp. 30

[3] M.J. Roy, R.J. Klassen, J.T. Wood: *Evolution of plastic strain during a flow forming process*, J. Mat. Process. Technol., 209, 2009, pp. 1018-1025

[4] C.C. Wong, A. Danno, K.S. Fong: *Deformation behavior in flow forming of cylindrical cups using finite element method*, Steel Res., 81, 9, 2010, pp. 710-713

[5] M.S. Mohebbi, A. Akbarzadeh: *Experimental study and FEM analysis of redundant strains in flow forming of tubes*, J. Mat. Process. Technol., 210, 2010, pp. 389-395

[6] B. Awiszus, S. Kleditzsch: *Acceleration of the FEM simulation of flow forming processes using modified initial values*, SPP1146: Modeling incremental forming processes, Final Report, Shaker Verlag, 12, 2010, pp. 255-272, ISBN - 978-3-8322-9532-5

[7] B. Awiszus, G. Herold, A. Trávníčková: *FMM simulation – A new approach for modeling incremental forming processes of the flow forming type*, Proceedings of 7th ICTP, Oct 27-Nov 1 2002, Yokohama/Japan, Japan Society for Technology of Plasticity, pp. 931-936

[8] M. Gur, J. Tirosh: *Plastic flow instability under compressive loading during shear spinning process*, J. Eng. Ind., 104, 1982, pp. 17-22

[9] J.W. Park, Y.H. Kim, W.B. Bae: *Analysis of tube-spinning processes by the upper-bound stream-function method*, J. Mat. Process. Technol., 66, 1997, pp. 195–203

[10] R. Ufer: *Modellierung und Simulation von Drückwalzprozessen*, Verlag Wissenschaftliche Scripten Zwickau, 2006, ISBN-13: 978-3-937524-43-6

[11] P. Ludwik: *Elemente der Technischen Mechanik*, Springer, Berlin, 1909

[12] T. Spittel: *Mathematische Formulierung der Fließspannung bei Kaltumformung*, Umformtechnik, 22, 6, 1988, pp. 258-267

[13] M. Hayama, H. Kudo: *Analysis of diametrical growth and working forces in tube spinning*, Bulletin of Japan Society of Mechanical Engineering, 22, 1979, pp. 776-784