FAST SIMULATION OF A FLAT CROSS WEDGE ROLLING PROCESS

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Key words: Fast Simulation, elementary methods, flat cross wedge rolling, process planning.

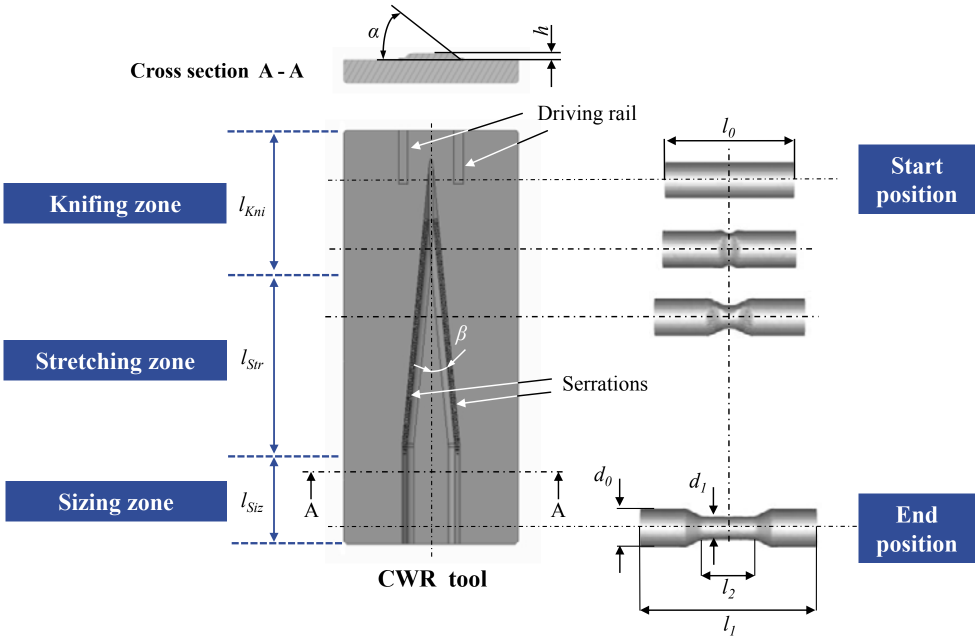
Summary. *In this paper, a new approach for a Fast Simulation of flat cross wedge rolling processes is presented. The approach is based on a preliminary research project of the Institute of Forming Technology and Machines (IFUM) of the Leibniz Universität Hannover, in which a software prototype for a Fast Simulation of a radial-axial ring rolling process was developed. Both simulations are based on geometric-kinematic models that allow a faster calculation of the material flow compared to the Finite Element-simulation (FE-simulation). The goal of the Fast Simulation for the flat cross wedge process is to support the designer in the challenging design phase of the flat cross wedge tool as well as in the planning phase of the process parameters. In this phase it shall be easier in future to determine the best geometric parameters for the design of flat cross wedge tools, to attain the necessary material flow and geometry, before starting with the first FE-simulation. With this preliminary information from the Fast Simulation it will be possible to reduce the number of iteration loops for the time-consuming FE-simulations of incremental forming processes.*

1 INTRODUCTION

To increase the efficiency in production processes regarding costs and time, one possible step is to use manufacturing processes with a high output because of the low cycle times and a high material utilisation. One manufacturing process that meets these criteria is the incremental metal forming process of cross wedge rolling (CWR). With CWR cylindrical blanks are deformed into axisymmetrical workpieces by moving the wedge shaped tools tangentially relative to the workpiece [1]. It is an efficient manufacturing process that is often used for the manufacturing of stepped axles and shafts as well as for preforming forged axles, shafts and piston rods (semi-finished products) [2].

One of the most widely used CWR-methods for industrial manufacturing processes is the flat cross wedge rolling [2, 3]. The flat cross wedge tool often consists of three forming zones. In Figure 1 a three zone flat cross wedge rolling tool is schematically illustrated. This consists of three forming zones, which are the knifing, the stretching and the sizing zone. In the first zone (knifing zone) the billet is driven and receives a V-shaped central cut. For the stabilization of the rotation and the positioning of the billet during the rolling process serrations are used in this and the following stretching zone [4]. In the knifing zone the wedge increases to the final height of the workpiece. In the second zone (stretching zone) the material is forced to flow to the ends of the workpiece, so that the shoulders of the shaft are formed. In the final sizing zone the workpiece is formed to its rotationally symmetric geometry [2, 5].

The material flow and the final geometry of the workpiece are influenced by geometric parameters of the CWR-tool and process parameters. These parameters are shown in Figure 1 and described in the following. The forming angle α controls the V-shaped slot in the knifing zone. The wedge angle β controls the amount of elongation and plastic deformation in the stretching zone. In the knifing zone the height h of the wedge defines how deep the blank is cut in radial direction, the total reduction of height as well as the area reduction of the workpiece. The length of the knifing zone l_{Kni}, the forming angle and the height of the wedge influence each other. The length of the stretching zone l_{Str}, the wedge angle and the length of the cross section l_2 correlate with each other. For a calibration of the final geometry and to remove the serrations from the previous stretching zone, it is important that the workpiece rotates at least once around its own axis. So the length of the sizing zone l_{Siz} has to be at least the circumference of the diameter d_0 [2, 5].



α = Forming angle
h = Tool height
l_{Kni} = Length of knifing zone
l_{Siz} = Length of sizing zone
l_0 = Initial length of billet
l_2 = Length of cross section
β = Wedge angle
d_0 = Initial diameter of billet
l_{Str} = Length of stretching zone
d_1 = Diameter of cross section
l_1 = Final length of billet

Figure 1: Important geometric parameters of a three zones flat cross wedge tool.

These geometric parameters can be summarized in a parameter set which is important for the design of the CWR-tool.

2 STATE OF THE ART

The design of the workpiece and CWR-tool can be divided in two main steps: The predesign and the detailed design step (Fig. 2).

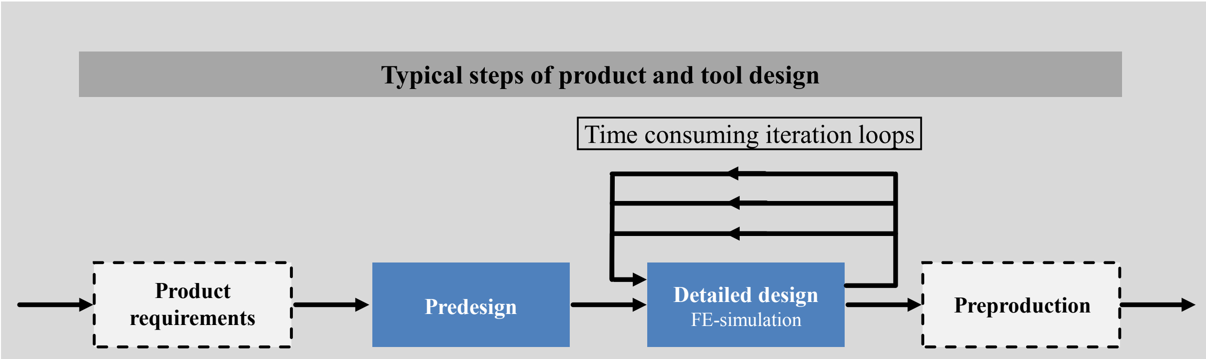


Figure 2: Steps of product and tool design for CWR.

Based on previously defined product requirements, a first draft of the billet and the corresponding CWR-tool is created by empirically based geometric and process parameters in the first design step, the predesign. In the following step, the detailed design the previously selected geometric parameters (e.g. forming angle and wedge angle of the CWR-tool) as well as process parameters (e.g. temperature of the billet and rolling speed) are tested inter alia regarding the material flow and the required forming force. Today these tests are done by FE-simulation so that costs for experimental tests can be saved and the best parameter set for the design of the desired contour of the CWR-tool and the CWR-process can be found faster. However, to find this best parameter set it is still necessary to test different sets even with the FE-simulation. One problem in the simulation of incremental forming processes, like CWR, is the long computing time. The calculation time for incremental processes can take up to several days or weeks for one calculation run and one parameter set [6]. This is due to the fact that the continuous new contact conditions between the tools and the billet as well as the remeshing of the billet contributes to the long computing times as well. This leads to many time consuming iteration loops.

Thus, other approaches to testing parameter sets in the phase of the CWR-tool predesign are necessary. At the Institute of Forming Technology and Machines (IFUM) of the Leibniz Universität Hannover a software prototype for a Fast Simulation of the incremental forming process radial-axial-ring rolling has already been developed in previous studies [7]. This software prototype allows, inter alia, to check the material flow before using the FE-simulation by varying different process parameters like roller feeds and to test chosen rolling strategies. This software is based on the so-called slice model that belongs to approaches of the elementary plasticity theory. With this software the calculation time of a few hours for one simulation on a commercial computer could be reached instead of one week by FE-simulation [7].

Based on the approach for the radial-axial-ring rolling process a further software prototype for a Fast Simulation of CWR-processes shall be developed in this research project. The software prototype for the Fast Simulation of CWR-processes shall be used in the design step (Fig. 3). The Fast Simulation shall enable the designer to test quickly whether the empirically based parameter set leads to the desired contour of the billet or not. If the empirically based parameter set does not lead to the desired contour, other parameter sets can be tested very fast with the software prototype, until a suitable parameter set is determined. In the detailed design with a suited parameter set the FE-simulation is used to determine further process parameters like the required forming force or the temperature of the blank. By means of the Fast Simulation the number of time consuming iteration loops by FE-simulation to check the material flow can be reduced.

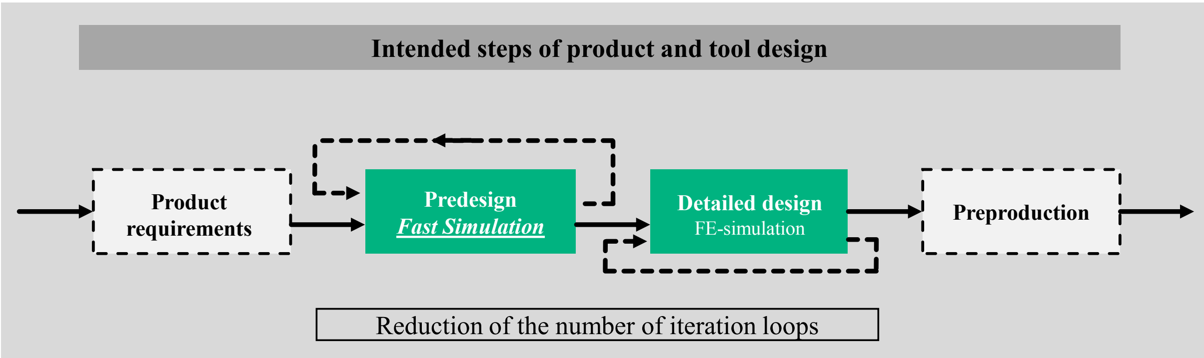


Figure 3: Steps of product and tool design with Fast Simulation software.

3 APPROACH TO A FAST SIMULATION OF CWR-PROCESSES

With the developed approach a Fast Simulation of the material flow of the billet and a prediction of the shape of the billet at different times of the CWR shall be possible. Therefore, it is previously necessary to identify geometric parameters of the billet and CWR-tool as well as process parameters that influence the material flow and the shape of the billet. Important parameters that have been identified are shown in Table 1 (cf. Fig. 1). Furthermore, an exemplary testing process is chosen. It is a flat CWR-process from the Institut für Integrierte Produktion Hannover (IPH) gGmbH [8, 9]. The values of the important parameters for the Fast Simulation of this process are listed in Table 1. The blank is made of the micro-alloyed stainless steel 38MnVS6 (EN 1.1303) and rolled at a temperature of 1,250 °C.

Table 1: Parameter set of the selected CWR-process.

Parameter	Value	Unit
Rolling speed v	0.3	m/s
Rolling time t	1	s
Initial diameter d_0	25.2	mm
Initial length l_0	90.6	mm
Initial diameter d_0	25.2	mm
Final length l_1	112.9	mm
Length of knifing zone l_{Kni}	74	mm
Length of sizing zone l_{Siz}	139	mm
Length of stretching zone l_{Str}	87	mm
Tool height h	5.7	mm
Forming angle α	25	°
Wedge angle β	7	°

After the previous identification and definition the geometrical-kinematic-model for the Fast Simulation software prototype is developed. It consists of the 3 steps (Fig. 4 b, c, d): Segmentation of the billet (Step 1), Meshing of the segments (Step 2) and Calculation of the material flow (Step 3).

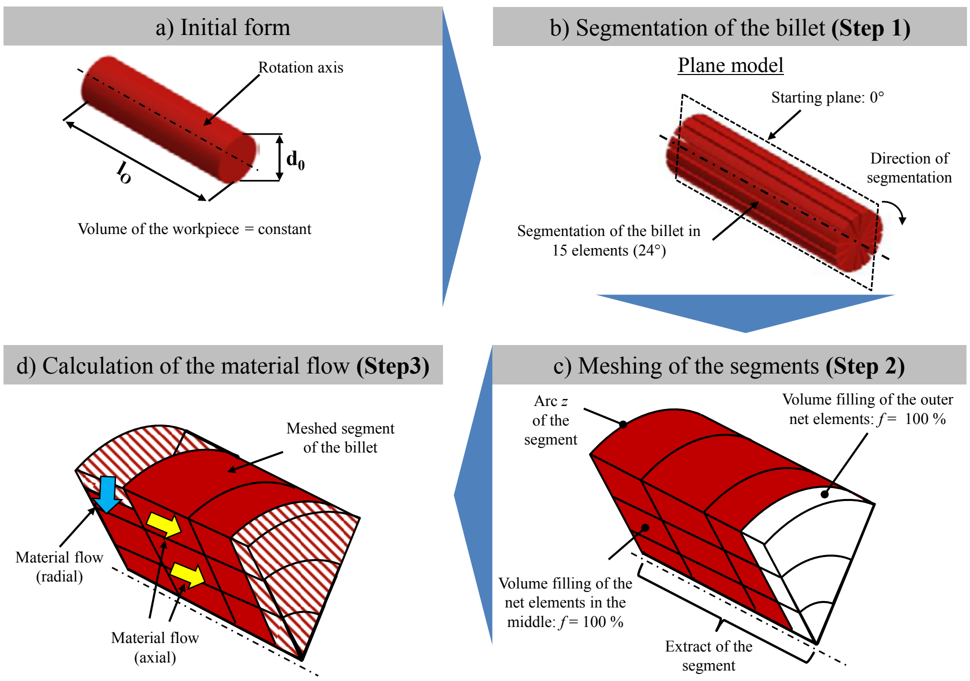


Figure 4: Methodical approach to the development of the Fast Simulation software prototye.

3.1 Segmentation and cutting (Step 1)

Based on the “consistent volume model” typical for metal forming processes and on the initial form of the billet (Fig. 4a), the existing slice model (cf. [7]) is transferred to a plane model in the first step “Segmentation of the billet” (Fig. 4b). Planes are generated every 24° through the middle axis of the billet so that the billet is segmented into 15 elements. The segmentation of the billet every 24° is empirically exact enough to map the material flow. With the initial diameter d_0 of the billet (cf. Table 1) and the segmentation angle of 24°, the length of the arc ($z \approx 5.3$ mm) between two planes is calculated. Transferring this value to the length of the forming zone (sum of the length of the knifing-, sizing- and stretching-zone l_{KSS}) of the CWR-tool, which is 300 mm, the CWR-tool can be cut from starting position to the end position into 56 planes of the equal distance of 5.3 mm (No. 1 - No. 56) and a plane (No. 57) with a distance of 3.2 mm to the previous plane. For a better visualization the lower CWR-tool is shown in Figure 5. These 57 cuts represent the 2D-contour of the CWR-tool at different steps of the rolling process.

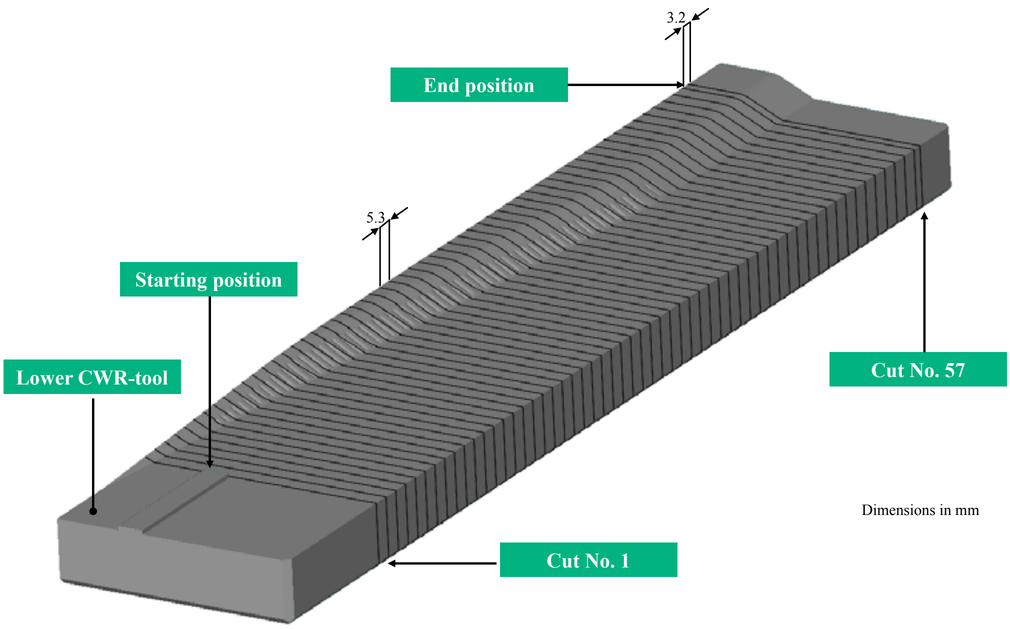


Figure 5: Segmented lower right CWR-tool

3.2 Meshing of the segments (Step 2)

In the following step “Meshing of the segments” (Fig. 4c) the segments of the billet and the 57 profiles of the tool are meshed by the use of a meshing algorithm. This has already been successfully used for the Fast Simulation of the radial-axial-ring rolling [8] and is adapted to the CWR-process. The 2D-contours of the billet and the upper CWR-tool are equally meshed with an edge length $a \in \mathbb{Z}^+$ in mm that can be defined with the software prototype. Because of the symmetry of the billet it is only necessary to calculate half (here: right) of it and to use only the right half of the CWR-tool. Positive integers for the edge length have been chosen for their simplicity regarding the addressing of the net elements, because of the positioning of a square in a 2D-Cartesian coordinate system. The position of a square can be described in this coordinate system by vector $V \in \mathbb{Z}^2$. Segments of billet and CWR-tool are defined as non-cutting, closed polygons: $P \coloneqq P_1, P_2, \ldots, P_n, P_i \in IR^2, 1 \leq i \leq n$. The first point of polygon is set in: $P_{1Billet} \coloneqq (0,0)$. During the scan of these polygons (billet and CWR-tool) with a defined resolution a, squared net elements are generated with the edge length a, which is identical with the resolution a. Thus, every segment of the CWR-tool receives its own net. The used meshing algorithm is shown in Figure 6.

```
1.P0 ∈ ℝ² with x := 0, y := 0;   //starting point for the polygon
2.V0 ∈ ℤ² with x := 0, y := 0;   //starting vector of the net element
3.net element N with x := 0, y := 0, resolution a and degree of filling f ∈ ℝ, 0 ≤ f ≤ 1;
4.Xmax = max {P1.x, P2.x,..., Pn.x}
5.Ymax = max {P1.y, P2.y,..., Pn.y}
6.while (P0.y ≤ Ymax) {
7.        while (P0.x ≤ Xmax) {
8.                if (test "square in polygon" with edge length a) {
9.                        if (square is completely in the polygon)
10.                               N.f := 1.0;
11.                       else
12.                               N.f := 0.5;
13.                       generate net at the position V0 the net element N;
14.               }
15.               V0.x := V0.x + 1;
16.               P0.x := P0.x + a;
17.       }
18.       V0.x := 0;
19.       V0.y := V0.y + 1;
20.       P0.x := 0;
21.       P0.y := P0.y + a;
22.}
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Figure 6: Used meshing algorithm for CWR after [10].

In the first line of the algorithm a starting point P_0 of the polygon and in the second line a starting position V_0 of the net element are defined. Furthermore, in the third line a first net element N is declared with coordinates (0,0), resolution a and degree of filling of a volume f. Every net element of the billet receives its own relative degree of filling of a volume $f \in IR, 0 \leq f \leq 1$ (Fig. 4c) describing to which extent a volume element is filled with material. The volume elements inside the billet are always filled 100 % with material. The degree of filling of the outer volume elements can vary between 0 % and 100 % during the simulation. If the degree of filling of the outer volume elements is 0 %, it is defined as non-existing.

CWR-tools are defined as rigid and therefore always have a degree of filling of 100 % and are positioned relative to the polygon of the billet. In the lines 4 and 5 of the meshing algorithm the maximum values of the x- and y-coordinates of the polygons (billet and CWR-tools) are defined under the condition that the polygons are closed. The loops in line 6 and 7 are introduced to guaranty the completeness of the polygon scans. The solution a defines the step size of the scan that is incremented in line 16 and 21. In line 8 a test “square in polygon-algorithm” [cf. 10] is run to analyse, if the actually scanned square is completely or partly located in the polygon (billet or CWR-tool) or just touching it. If the square is totally located in the polygon it receives the degree of volume filling of 100 % (line 9 and 10). If the square is partly in the polygon a volume filling of 50 % is allocated to the net element. These 50 % are a first simplification to approve reality and will be specified in the future. If the square is outside or just touching the edge of the polygon (billet) no net element is generated. The result of the meshing algorithm is an amount of net elements for billet segments and CWR-tool cuts as well as necessary whole number 2D-coordinates and a degree of volume filling for each of these elements.

3.3 Calculation of the material flow (Step 3)

In the next step a further algorithm that is actually in the development process starts with the calculation of the material flow (Fig. 4d). The functioning of the algorithm is exemplarily described in the following. Starting point for the example is a cut of a CWR-tool (e.g. cut No. 34) and the corresponding cut of the formed billet at a late stage of the CWR-process. The CWR-tool and the billet remain in contact and are remeshed from the previous calculation step of the material flow algorithm (Fig. 7a).

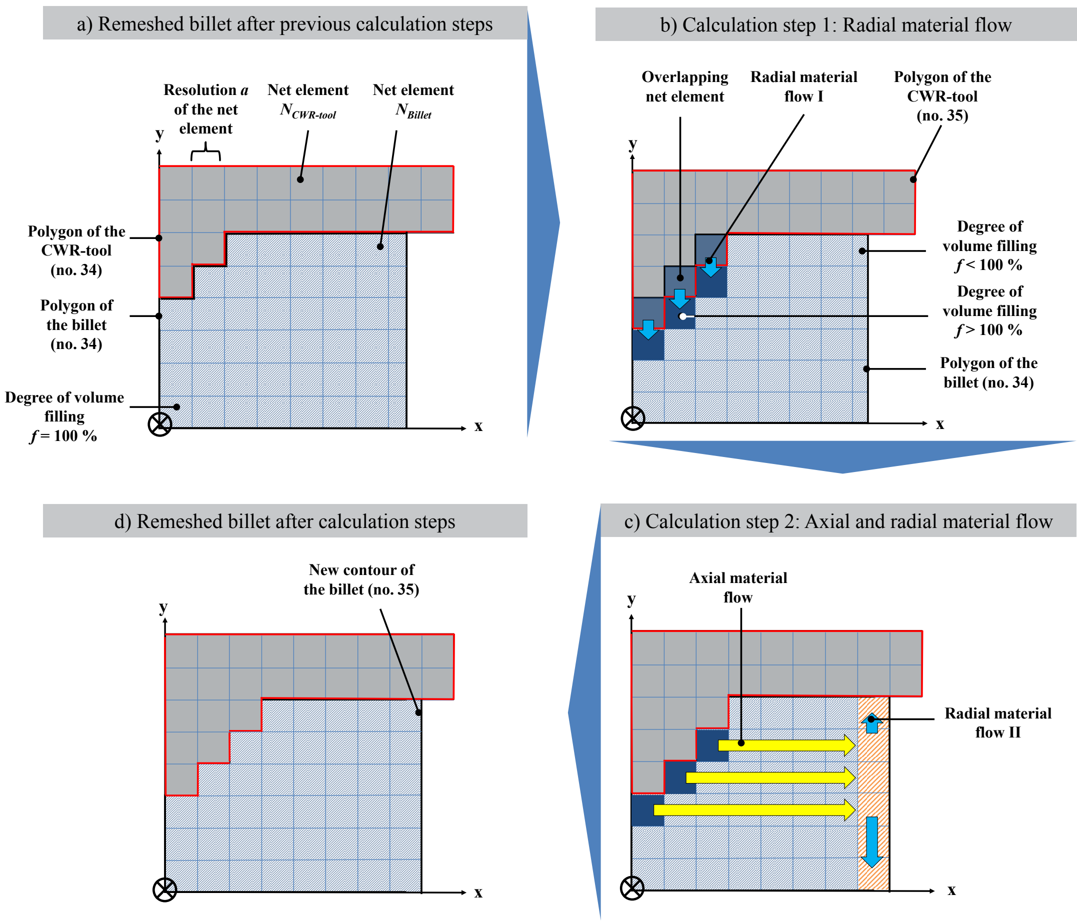

Figure 7: Approach to the simulation of the material flow (cf. Fig. 4d).

In the next calculation step of the material flow algorithm the meshed cut No. 35 of the CWR-tool is positioned in the coordinate system. The net elements of the billet with the same coordinates as the net elements of the CWR-tools ($N_{Billet} = N_{CWR\text{-}tool}$) will be completely relocated (radial material flow I) in the neighbouring net elements of the billet in radial direction (Fig. 7b). These neighbouring net elements contain temporarily a degree of filling of the volume element of f > 100 % (here: 200 %). In the next step (Fig. 7c) a compensation for the degree of filling of the volume takes place by the algorithm checking the degree of filling of the volume of the adjacent net element. This control is carried on until the degree of filling is less than 100 %. Meanwhile material is easily relocated in the latest checked element (degree of filling < 100 %) due to the amount of material removed at the beginning of the step. By means of this procedure axial material flow can be realised.

Based upon the results of the FE-simulation it can be idealized that the removed material is uniformly attached to the outermost net elements in radial direction during the CWR-process. For a uniform filling of the outer net elements in radial direction with the Fast Simulation the number of net elements that represent the outer contour of the billet are determined (here: 6 outer net elements) (Fig. 7c). Then the cumulated removed material (dimension: degree of volume filling) is uniformly spread to the previously found outer net elements of the billet. Outer net elements with f = 50 % are filled with material until f = 100 % (radial material flow II). If there is still material left, new equally filled net elements adjacent to the outer net elements of the billet are generated. In the second last step all net elements of the billet with f = 0 % are deleted. Finally, the new polygon of the billet is remeshed to allocate coordinates to the new polygon (Fig. 7d) and the material flow algorithm can restart.

4 SOFTWARE PROTOTYPE FOR A FAST SIMULATION OF CWR-PROCESSES

Based on the previously presented approach a user-friendly Fast Simulation software prototype named “CroSim” (Cross wedge rolling simulation) will be developed. With the software prototype the designer will receive information about the expected shape of the billet during and after the CWR-process based on his previous design of the CWR-tool and his selection of process parameters. In general, the FE-software consists of a pre-processor, solver and post-processor. This structure will be adapted to the software prototype “CroSim” (Fig. 8).

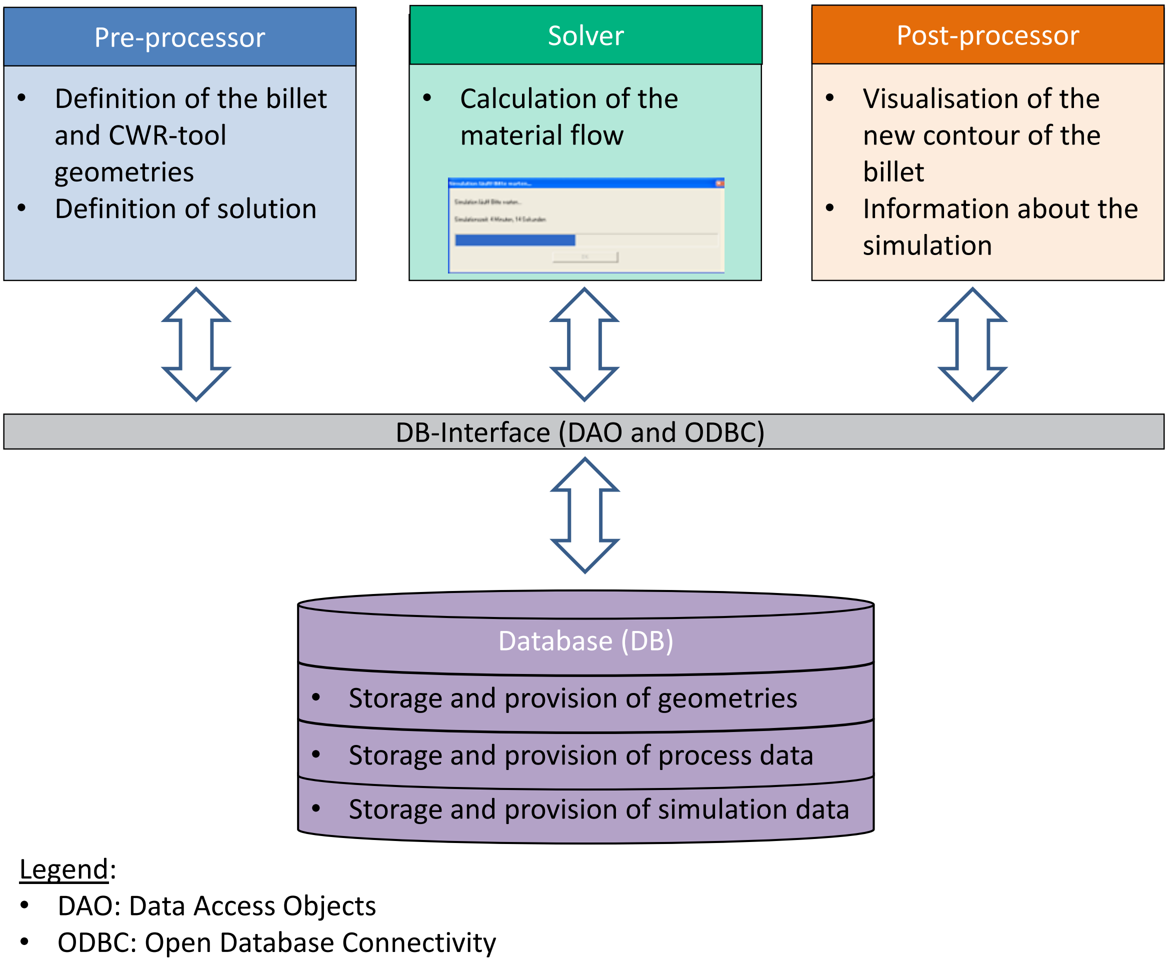

Figure 8: Structure of the software prototype “CroSim”.

With the Graphical User Interface (GUI) of the pre-processor of “CroSim” the designer will define the starting geometry of the billet, import and prepare the different contours of the CWR-tool and visualize them. The contours will be stored via an Open Database Connectivity interface in a Microsoft® Access database. Furthermore, the solution *a*, the rolling time *t* and the rolling speed *v* will also be stored in this database. The solver of “CroSim” is currently programmed in the coding language C++ with the help of the Microsoft® Visual Studio environment. The solver imports the data (geometries, process and simulation data) via Data Access Objects interface from the database and calculats the material flow. With a GUI for post-processing the 2D-contour of the billet at every step of 57 cuts of the CWR-tool will be visualized by importing these data from the database.

5 CONCLUSION

In this paper an approach to a Fast Simulation named "CroSim" for the incremental metal forming process: flat cross wedge rolling is presented. This new approach allows for a faster design of CWR-tools by calculating the expected material flow in a shorter time than with the FE-simulation. With the help of "CroSim" the designer will gain a fast insight into the best geometric and process parameters for the design of the CWR-tool. This knowledge will save much time in the future since numerous time-consuming FE-simulations will become obsolete. Nevertheless, it is still necessary to use FE-simulation to determine important parameters like the required forming force. The main focus in further research work is on finishing the development of the software prototype and validating the results from "CroSim" with results from experimental and numerical (FE-Simulation) studies. Furthermore, it is thinkable to adapt the approach to further flat CWR-processes with tools that have multiple wedges and different process parameters like rolling speed and rolling time.

ACKNOWLEDGEMENT

The authors thank the German Research Foundation (DFG) for its financial support of the IFUM project "Entwicklung eines geometrisch-kinematischen Modells zur schnellen Simulation von Querkeilwalzprozessen" with the project number BE 1691/127-1. Furthermore, the authors thank the European Commission for the funding of the IPH project (project number: 221967) within the 7th Framework Programme (Research for the Benefits of SMEs; Call identifier: FP7-SME-2007-1). Further thanks go to B. Sc. Minh Triet Ly who supports the meshing algorithm within the project in the phase of programming.

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