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FE - Simulation of Thin Strip and Temper Rolling Processes

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Abstract

Within the production chain of cold-rolled flat products skin-pass and temper rolling represent the final forming stage, in which material and surface properties as well as flatness are tailored to satisfy even the most demanding customer requirements. Almost all skin-pass and temper-mill setups are based on offline calculations, supplemented by trial and error procedures during operation. To minimize strip segments that do not match the prescribed tolerances, which occurs especially after changes in sheet sizes, it is of vital importance to incorporate appropriate offline and online models to the automation structure of such rolling mills. Key objectives of adequate models are the precise determination of the rolling force, of the roughness transfer and of the roll-flattening behaviour. As is well known for thin sheet, foil and temper rolling processes, the simplified assumption of a circular arc of contact breaks down. Therefore, the correct non-circular surface contour of the work roll has to be determined simultaneously with the resulting contact pressure distribution between strip and work roll. To attain a comprehensive understanding of these underlying process details, and to check and tune semi-analytical model approaches (cf. e.g. [7-10]), highly sophisticated numerical approaches based on the method of finite elements have been performed by utilizing the non-linear capabilities of Abaqus Standard and Explicit [1]. Due to extremely short contact lengths in temper rolling processes, a very fine spatial discretization is essential, often leading to several hundred thousand degrees of freedom even for plane strain calculations. Special emphasis has to be put on work roll flattening [6] and on the formation of contained plastic flow regions [2].

1 Introduction and Survey

Rolling processes can be considered to be key steps within the production of steel. Therefore, the development of highly sophisticated mathematical process models is a vital precondition for manufacturing high quality products satisfying narrow tolerance demands. By performing systematic parameter studies and regression methods, sets of characteristic curves can be obtained, which serve as an input for online control and process automation systems. Mathematical online and offline models, validated against each other and calibrated with real process data, are essential to determine proper mill setups, to improve the quality of the rolled product, to control the online process of metal forming, and to optimize the mill throughput and yield (i.e. minimize scrap).

In strip mill operations, the temper rolling of steel represents the final stage within the production chain of cold-rolled flat products. With annealed strips to be subsequently formed, temper rolling provides a slight reduction in thickness, and thereby eliminates the yield point elongation in the stress-strain curve of the steel. This permits the material to be formed without developing Luder's bands. Besides, temper rolling is also used to improve the surface quality of the strip and the flatness properties. To optimize these final properties of cold rolled steel, the elongation of each strip product must be strictly controlled to a certain value in the temper rolling process. Therefore, an accurate elongation control system, which is based on precise mathematical process models for the prediction of roll force, torque and forward slip is essential. The key criteria in skin-passing are surface cleanliness and roughness, which are important for subsequent painting, welding and deformation processes. An important issue is to keep the surface of the work rolls clean to prevent that particles are imprinted into the strip in the roll gap. This task can be accomplished by utilizing either the conventional wet temper system, where a water-agent mixture is sprayed into the entry of the roll bite, or by the dry temper technique *(Fig. 1)*, where a combination of rotating and oscillating brushes is pressed slightly against the roll surfaces thereby cleaning all particles sticking to the roll surfaces [7].

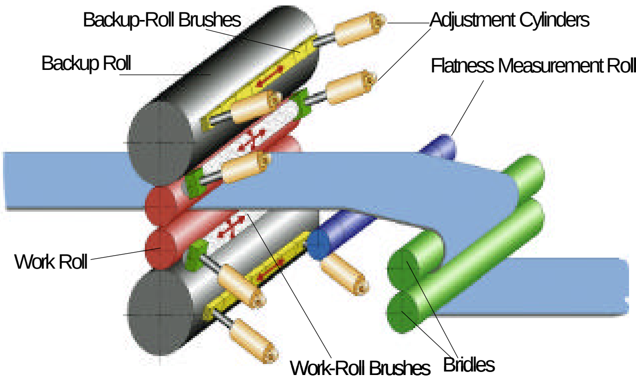

Fig. 1: State of the Art Dry Temper Rolling Equipment (cf. [7])

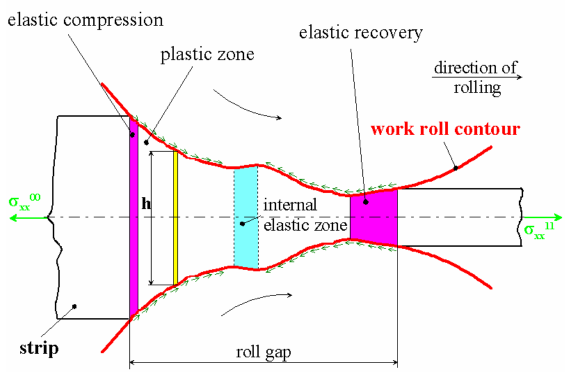

Fig. 2: Decomposition of the deformation zone inside the strip in elastic and plastic regions

For temper rolling processes the conditions inside the roll bite are significantly different from those of usual hot or cold rolling processes in reversing or tandem mills. The work rolls are significantly deformed in a way similar to that of Hertzian contact. The strip elongation (or reduction) is of the order of one percent (~0.2%–2%), the deformation is highly localized and a significant elastic spring-back of the strip can be observed. Therefore, standard circular arc roll gap models (e.g. Bland Ford Ellis combined with an effective Hitchcock curvature) do not apply. Such models predict huge pressure increases in the roll gap when rolling thin gauges due to the frictional forces present throughout the roll gap, combined with the simplifying assumption of a circular arc of contact. A significant improvement was achieved by Jortner et al. [6] describing the work roll deformation in radial direction using influence functions. In 1987 Fleck and Johnson [2] published a theory appropriate for the rolling of thin strips and foil. Their theory omits the use of simplifying presumptions on roll-flattening geometry, which can be considered as main reason for failure when applied to thin-gauge rolling. Besides, their model predicts the occurrence of an intermediate "contained plastic flow" zone, where a flat work roll surface parallel to the strip middle plane occurs.

Because of the trend to thinner and harder strips, and due to the fact that the contact length is very short for small strip elongations, the development of improved offline and online models for temper rolling is essential. Enhanced models developed recently [3, 7-10] include an elastic compression zone at the roll gap entry, an elastic recovery zone at the exit and a plastic zone in between, whereby elastic regions are also allowed to arise between plastic zones (*Fig. 2)*. This ensures that a contained plastic flow zone is included automatically in the model and need not be postulated a priori. To ensure praxis-relevant results a systematic comparison and calibration of these highly sophisticated semi-analytical models with real process data and with results obtained by Finite element simulations is absolutely necessary. Transient dynamic Finite Element simulations, which are of course much more calculation time consuming than problem-adequate optimized steady-state 1D solution procedures (nevertheless highly non-linear and ill posed problems), enable a deep insight into the underlying process details and yield valuable feedback to the qualitative solution behaviour.

2 Method of Analysis

To obtain a deeper understanding of the occurrence of contained plastic flow regions inside the roll gap for temper rolling processes with small strip elongations, we decided to perform a transient dynamic simulation of this process by utilizing the non-linear capabilities of the software package Abaqus Explicit [1]. Due to the geometric properties of the setup (strip width of 1288 mm), a plane strain 2D simulation of the vertical mid-plane suffices. Note that on account of a horizontal mid-plane symmetry property only the upper work roll and the upper half of the strip have to be simulated. A strip of initial thickness of 500 µm is rolled to an elongation of 0.5% by an elastically deformable work roll with undeformed radius of 295 mm and prescribed angular velocity of 22.63 rad/s. The strip is modeled as an elasto-plastic 2D solid body. It should be emphasised that a strip reduction of 0.5%, i.e. the upper half of the strip is reduced from 250 µm to 248.7 µm, is accomplished by lowering the center of the work roll by 50 µm, i.e. the vertical work roll shift exceeds the strip draft by a factor 40. At least 5 elements in (half) thickness of the strip are necessary to obtain reliable stress and strain distributions inside the strip. Back and front tension stresses of 25 and 43 MPa, respectively, are applied to the inlet and outlet cross section of the strip and are kept fixed during the whole simulation. The initial velocity of the strip is put to 400 m/s, which coincides with the initial circumferential velocity of the work roll surface and ensures minimum possible strip element distortions at the initial phase of the simulation, when the strip is pulled into the roll gap. The yield stress curve includes strain hardening. For zero logarithmic strain the yield stress is assumed to be 400 MPa, increasing to 440 MPa for 1% strain, 500 MPa for 2.5% and up to 800 MPa for an equivalent strain value of 10%. For the first simulation-runs a strain rate dependence was neglected but will be incorporated in future investigations. The Young's modulus of the strip is chosen as 185 GPa and 225 GPa for the work roll. The Poisson's ratio for steel is ν=0.3 and the mass density takes the value ρ=7.85 kg/dm^3. The friction between the strip (slave) surface and the work roll (master) surface is modeled by utilizing the Coulomb friction law with a friction value of μ=0.15. In Abaqus Explicit the kinematic surface interaction algorithm with hard overclosure (describing the normal contact behaviour) turned out to be significantly superior to the penalty formalism, where an inevitable penetration of the master work roll surface into the strip lead to an extreme distortion of the strip contact surface elements.

Due to the very short contact lengths an extremely fine discretization of the work roll sleeve near the contact region is essential to obtain reliable and praxis-relevant data. In order to calculate at least 20 stress and displacement values along the non-circular arc of contact, a value of 200 µm or even shorter has to be chosen for the spatial discretization length of the work roll master surface. As the corresponding strip slave surface element length has to be chosen shorter, i.e. about 50-100 µm, the stable time increment for explicit time integration turns out to be of the order of 10^{-9} sec. (determined by Abaqus Explicit without mass-scaling) and for implicit methods of about 10^{-7} sec. Numerical considerations pointed out that at least 5-10 contact lengths have to be rolled, until a well pronounced steady state is reached. This results in a real process time of at least 4-8 ms for the test case under consideration. Therefore, the utilization of implicit solution concepts (Abaqus Standard) is not appropriate due to the extremely large number of intermediary linear stiffness equations that have to be solved, whereas explicit dynamic algorithms (Abaqus Explicit) are much better suited for this class of problems. Moreover, the memory requirements in Abaqus Explicit are one order of magnitude less compared to the Standard simulation variant. To speed up the calculation, mass scaling was employed and will be discussed in more detail in the next section. Special emphasis has to be put on an adequate modeling of the elastically deformable work roll *(Fig.3)*. The inner ring of the work roll is modeled as rigid body driven by an angular velocity constraint condition imposed on the reference point in the work roll centre. Previously performed systematic studies [4, 5] pointed out that such a simplification does not adulterate the deformation behaviour of the work roll sleeve as long as the radius of the inner rigid body region remains small compared to the outer work roll radius. On account of the very fine discretization of the work roll sleeve, the overall number of degrees of freedom would become very large for the case of an axially symmetric mesh, leading to a system with several 100 000 degrees of freedom. Therefore, only a 30° sector of the work roll sleeve was meshed very fine, resulting in a dramatic reduction of the number of degrees of freedoms (a total of 119 000 variables for the whole model incl. strip) without significant loss of numerical accuracy. The underlying work roll partition concept is represented in *Fig. 4*. The transition from a coarse structured inner mesh to ever finer outer meshes is performed by using concentric layers of triangular elements such that the mesh compatibility condition is never violated, as can be seen in *Fig. 5*. A detailed view of the work roll sleeve and the transition to coarser mesh regions in both circumferential and radial directions is given in *Fig.6*.

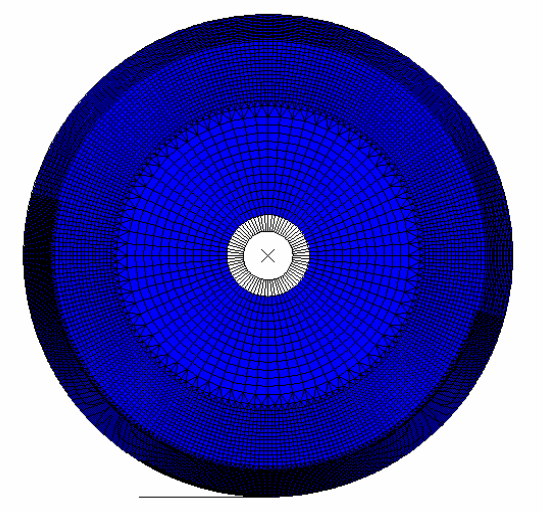

Fig. 3: Combined structured (quadrilateral) and free (triangular) meshing concept for the elastically deformable work roll

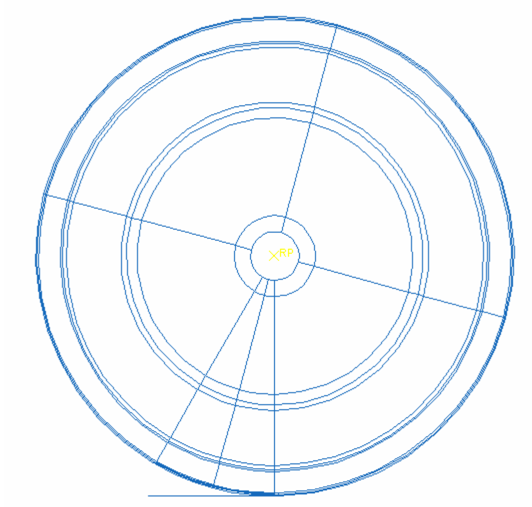

Fig. 4: The underlying work roll partitions to reduce the overall number of degrees of freedom without significant loss of accuracy

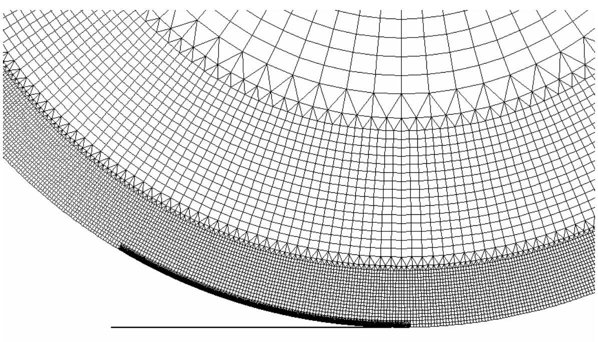

Fig. 5: Transition between coarse and fine meshed regions by triangular elements

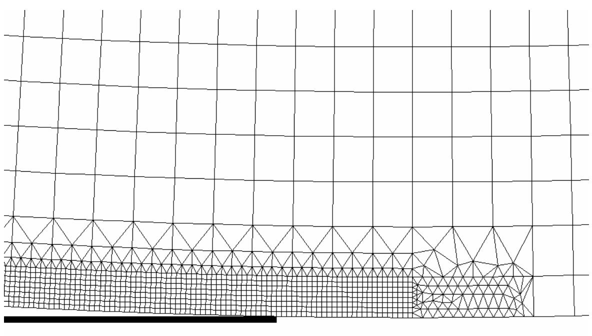

Fig. 6: Detailed view of the relevant fine discretized work roll sleeve sector

3 Numerical Results

The temper rolling process under consideration, as specified in the preceding section, was simulated by utilizing Abaqus Explicit. To obtain reliable steady state results, at least 5-10 deformed contact lengths have to be simulated. For this test case with a strip velocity of about 6.67 mm/ms, the rolling of a strip length of 150 mm takes approximately 22 ms real process time. This requires about ~10^6-10^7 time increments, as the stable time increment is of the order of ~10^{-8}-10^{-9} s (estimated by Abaqus Explicit), leading to a simulation calculation time of several days. To speed up the calculation mass scaling turned out to be very attractive. However, results obtained by choosing high mass scaling factors have to be analyzed with due care and lead to fast wrong answers, as is obvious from *Table 1*.

Mass scaling factor [dim.less]	Number of increments [dim. less]	Mises stress Max. in roll [Mpa]	Mises stress Max. in strip [Mpa]	Gap entry position [mm]	Gap exit position [mm]	Proj. Gap Length [mm]	Strip exit thickness [µm]
1	509262	498	444	-2.46	2.27	4.72	247.83
10	161040	509	435	-2.45	2.35	4.80	248.05
100	50923	530	427	-2.54	2.32	4.86	248.58
1000	16584	1012	562	-4.56	3.89	8.45	243.79
10000	5431	2565	800	-9.97	8.22	18.20	230.11

Table 1: Comparison of some relevant process data, obtained by different mass scaling values and evaluated at the process time 2 ms, when a strip length of 13.35 mm is rolled.

For this transient dynamic simulation, where an elastically deformable work roll and an elasto-plastic strip (and of course contact modeling in between) are involved, a fixed mass scaling factor of 100, applied to the whole model at the beginning of the simulation, proved to be a satisfactory compromise between accuracy and calculation time, where the latter quantity is reduced by a factor of 10 compared to no mass scaling.

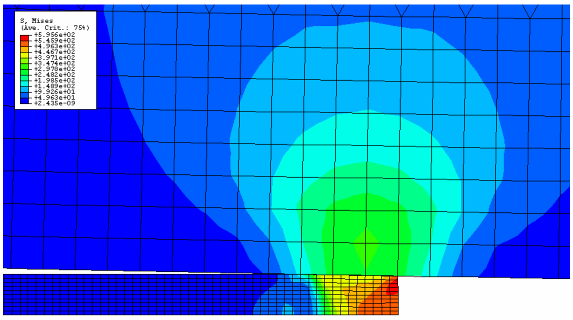

Fig. 7: Mises stress distribution inside the strip and work roll after 0.1 ms of process time

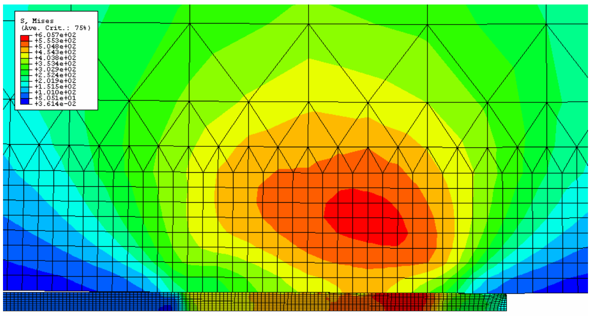

Fig. 8: The same distribution after 1 ms process time

Further advanced simulation techniques available in Abaqus Explicit include adaptive meshing on either Lagrangian or Eulerian domains, which turned out to be very beneficial for those test runs, where significantly higher strip reductions were prescribed. One of the most critical aspects is the accurate determination, whether a steady state has already been reached. For the class of rolling simulations treated in this context it turned out that a reliable criterion for steady state detection is the ratio between the increase of the kinetic energy per unit time and the dissipated power. Provided that this ratio is small compared to unity a steady state scenario can be assumed.
Of particular interest in dynamic transient FE simulations is the development of stress and deformation fields during the time evolution. The Mises stress distributions inside the strip and the relevant part of the work roll are represented in *Fig. 7* and *Fig. 8* after 0.1 ms and 1 ms real process time, respectively.

The stationary Mises stress distribution after 20 ms process time, when already 27 contact lengths are rolled, is depicted in Fig. 9. An enlarged view of the relevant part inside the work roll is given in Fig. 10. These results meet the expectations and justify the work roll modeling concepts outlined in the preceding section.

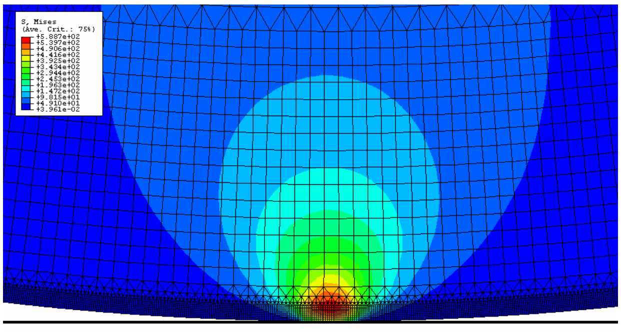

Fig. 9: Stationary Mises stress distribution after 20 ms of real process time

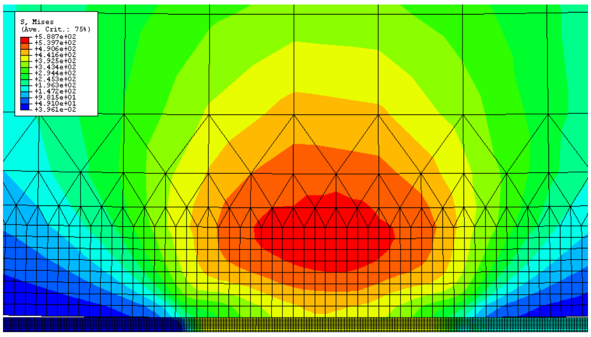

Fig. 10: Detailed view of the steady state Mises distribution inside the work roll

This FE-simulation yields valuable information about the emerging stress-, velocity- and displacement fields inside the work roll and the roll gap. Moreover, the non-circular arc contour of the work roll is determined simultaneously with the corresponding contact pressure and shear stress distributions. A typical pressure profile for steady-state dry temper rolling is shown in *Fig. 11*, together with the corresponding shear stress distribution in *Fig. 12* for the case of Coulomb friction with a friction coefficient μ=0.15.

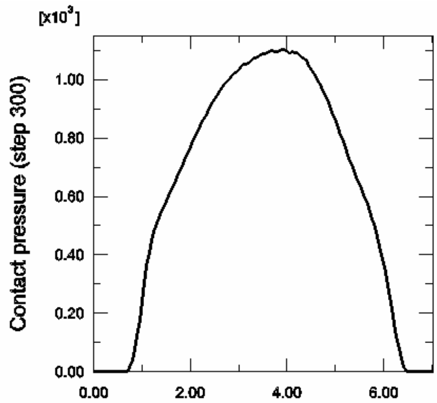

Fig. 11: Dry temper rolling steady-state contact pressure distribution along the arc of contact

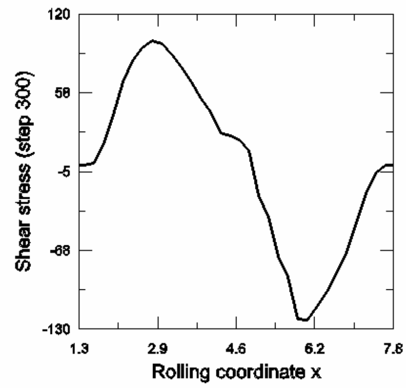

Fig. 12: The corresponding shear stress distribution for the case of Coulomb friction with μ=0.15

The same contact and shear stress distributions can be obtained by an evaluation along the path of a selected node at the strip surface when moving through the roll gap. These results are depicted in *Fig. 13* and agree extremely well with the ones taken at one point in time as represented in *Fig. 11* and *Fig. 12*. This coincidence fully confirms that a steady state has been reached. The stationary work roll surface contour is shown in *Fig. 14*, and the corresponding vertical and horizontal strip surface displacement fields (relative Lagrangian representation) are depicted in *Fig. 15* and *Fig. 16*, respectively. A well pronounced "contained plastic flow" zone inside the roll gap can be identified, where the contact surface contour is largely parallel to the abscissa and no strip reduction occurs. Inside this region the slip rate FSLIPR1, i.e. the slip velocity component in tangent direction, remains (approximately) zero along the contact line, as shown in *Fig. 18*, and the accumulated slip displacement FSLIP1 is almost constant inside this region, as is represented in *Fig. 17*.

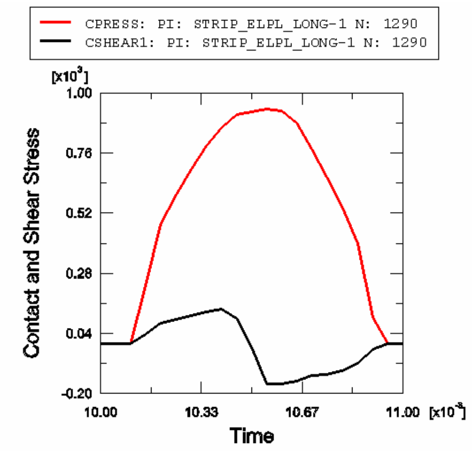

Fig. 13: Contact pressure and corresponding shear stress values acting on a selected node while moving through the roll gap

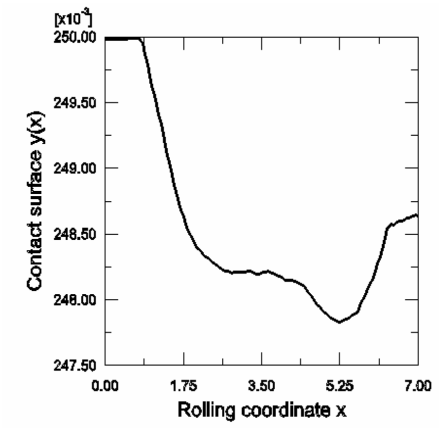

Fig. 14: The deformed steady state contact surface contour between the work roll and the strip inside the roll gap

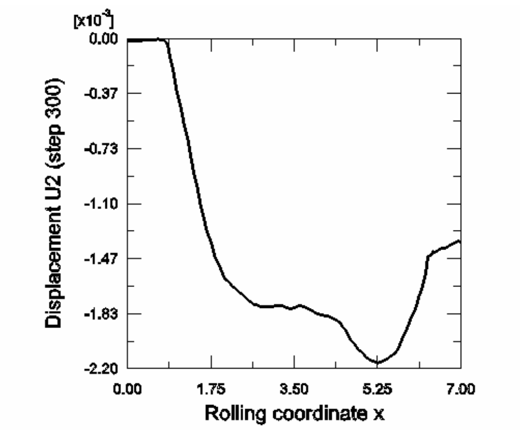

Fig. 15: The vertical strip displacement component U_2 for the steady case inside the roll gap

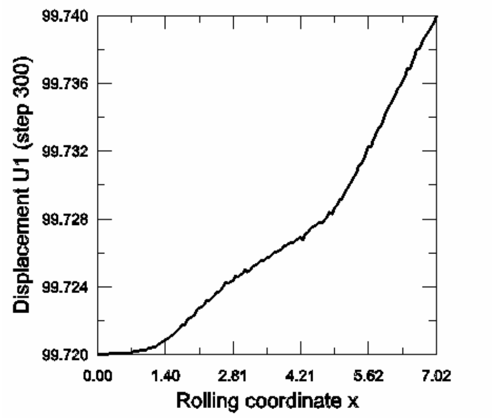

Fig. 16: The corresponding relative Lagrangian horizontal displacement component U_1 of the strip surface inside the roll gap

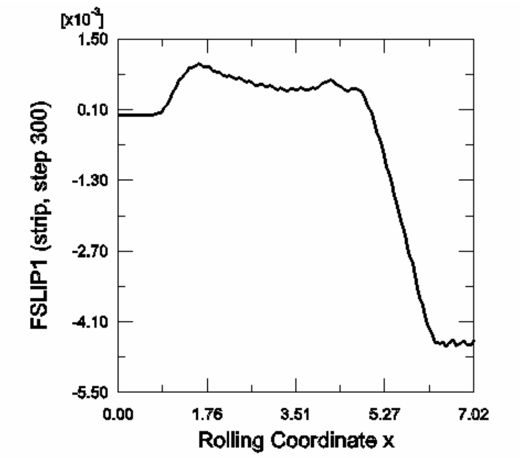

Fig. 17: The accumulated slip displacement component FSLIP1 along the contact surface for the steady-state case

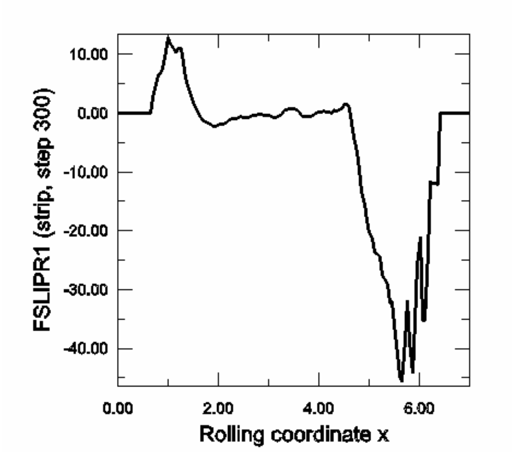

Fig. 18: The corresponding contact slip rate in longitudinal direction FSLIPR1 along the arc of contact for the steady state case

4 Conclusions and Future Prospects

In the present study a typical temper rolling process was simulated by utilizing the finite element package Abaqus Explicit [1]. Such investigations yield valuable information about the stress-, velocity- and displacement fields inside the roll gap. Moreover, the non-circular arc contour [5-7] of the work roll is determined simultaneously with the corresponding contact pressure and shear stress distributions, and a "contained plastic flow" zone [2-4, 7] inside the roll gap is identified. Due to the very short contact lengths an extremely fine discretization of the work roll sleeve near the contact region is essential to obtain reliable and praxis-relevant data. Further research objectives comprise systematic parameter studies of the temper rolling process and a critical analysis of the results calculated by FE-simulations. The data obtained by using Abaqus Explicit will be validated against real process data and compared with results determined by highly sophisticated semi-analytical models based on an extended version of the Jortner Green's function approach [5, 6] for the elastic work roll deformation, combined with an enhanced version of the Fleck Johnson [2, 7-10] strip model including elastic compression, recovery and contained plastic flow regions.

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