Hot Rolling Simulation of

Aluminium Alloys using LS-Dyna

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Abstract

Aluminium and its alloys are widely used and applications of aluminium alloys can be found in all kind of industries, from packaging to transportation, from consumer electronics to architecture and lighting. In order to obtain a better understanding of the production process of aluminium alloy plates and sheets AMAG rolling GmbH strengthens the use of coupled thermo-mechanical finite element methods in combination with microstructure based user defined material models. The presented work shows a hot rolling simulation, which is an important step of the process chain. A detailed overview of 2D and 3D models for multi pass simulations is given and a graphical user interface for an automated simulation setup is presented. With the help of a python based routine the virtual billet is trimmed and re-meshed after each rolling pass in order to reduce the computational time. A comparison of the implicit simulation to the explicit simulation regarding the computational time is made and some simulation results are shown. Furthermore a comparison of the obtained rolling forces and temperatures between measurements of the hot rolling mill and simulation is given for an industrial pass plan.

1 Introduction

Modelling methods have been applied to many different aspects of the fabrication of aluminium products [1]. Increasing computational resources and improved modelling methods make modelling methods even more attractive. In this paper, a coupled thermo-mechanical simulation of the hot rolling process is presented. The simulation is optimized to deliver reliable results in the most efficient way with respect to computation time. The simulation is part of the company's strategy towards the so-called "Through-Process-Modelling" of aluminium plates and sheets. An important aspect of this strategy is the emphasis, which is put on using physically sound models to describe the evolution of microstructure - phenomenological approaches should be avoided as far as possible.

Hot rolling is one of the first steps of the production process chain of aluminium alloys. The billet is passed several times through a pairs of rolls to reduce the thickness to a certain level. The massive deformation has a major impact on microstructure evolution. Gradients in the microstructure may arise due to the inhomogeneity of the deformation in the roll gap. Precise predictions of microstructure and deformation gradients across the billet require specific modelling methods. In the following, the simulation scheme will be presented. Special emphasis is put on the virtual trimming operation. Simulation results for rolling forces and temperatures as well as deformation fields at the edge of the billet will be shown and compared to measurements from the industrial process. Furthermore, results on the inhomogeneity of strain fields across the billet will be given.

2 Hot rolling simulation

2.1 Simulation scheme for hot rolling

Depending on the aluminium alloy and rolling strategy an industrial pass plan could consist of more than 30 rolling passes. It is obvious that to manually setup such an industrial pass plan is time consuming and prone to error. An automatic simulation setup supports the user (even if the user has no CAE experience) with a graphical user interface. The simple GUI collects the user input, for example which aluminium alloy and rolling mill is used, some general selections regarding simulation setup (2D or 3D) have to be made and the process parameters (pass plan, velocity etc.) have to be

defined. With this input an automatic simulation setup is possible, which follows the simulation scheme as shown in Figure 1. With this scheme a simulation of an industrial multi pass hot rolling simulation can be setup easily.
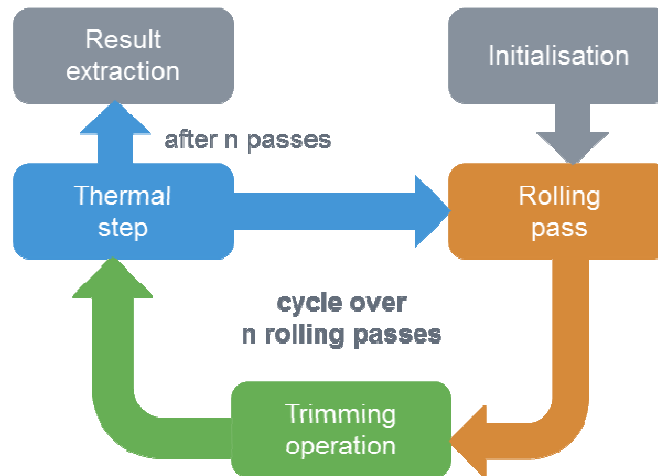

Fig.1:   Simulation scheme for multi pass hot rolling simulation

The first step is the initialisation, which includes a fully automatic mesh and material card generation. The mesh generation is based on a LS-PrePost command file, which is generated by a python routine and the user input for the billet dimensions and format. Depending on the chosen aluminium alloy a user defined material card is generated. Thereby a material database for several alloys is provided by the GUI including all relevant parameter for the user defined material model. In addition a keyword file for each rolling pass is created including the motion of billet and rolls, several solver settings, contact definitions, thermal boundary conditions etc.. After the initialisation the first rolling pass simulation starts to run, whereby implicit time integration scheme of LS-Dyna is used. Only a fraction of original billet length is used to reduce the computational time. In order to take the process time for the whole billet length into account the deformation step is followed by a thermal step. Between rolling and thermal step a trimming, re-meshing and mapping of the billet is performed. The python based routine is described below in detail. So each pass consists of a rolling simulation, followed by trimming the billet and ends with a thermal simulation. An automatic result extraction for the main and most interesting material properties of the billet is followed after the last thermal pass is finished.

2.2   General model setup

For a general rolling simulation a 2D model using plane strain elements is sufficient. The 2D model represents thereby the center of the billet with respect to the width direction. If the behaviour of the billet edge is of interest, a 3D solid mesh is needed. Only a quarter of the billet is considered in order to reduce computational time. As shown in Figure 2 the billet is separated into three ***PART** definitions. This allows to define different material properties and to take the precipitates and porosity distribution of the casting process into account. A ***MAT_USER_DEFINED_MATERIAL_MODELS** is implemented into LS-Dyna solver where the strain rate and temperature dependent flow stress is calculated according to a dislocation density based flow model of Kocks-Mecking type [2]. Additionally, a recrystallization model [3], a void evolution model [4] and a failure model [5] complement the user defined material model.

Due to the fact that the billet temperature varies during hot rolling, temperature dependent values for the heat capacity and heat conductance are defined by the keyword ***MAT_THERMAL_ISOTROPIC_TD_LC**. The billet is accelerated within 5.0 ms and moves towards the rolling gap with the constant rolling velocity. As contact definition between billet and rolls a ***CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_THERMAL** for 2D and a ***CONTACT_FORMING_SURFACE_TO_SURFACE_MORTAR_THERMAL** for 3D solid mesh is used. The range of thermal coefficients and friction are summarized in Table 1. The rolls are treated as rigid bodies. The infeed and the rotation of rolls is applied by using two separate ***BOUNDARY_PRESCRIBED_MOTION_RIGID** definitions for each roll.
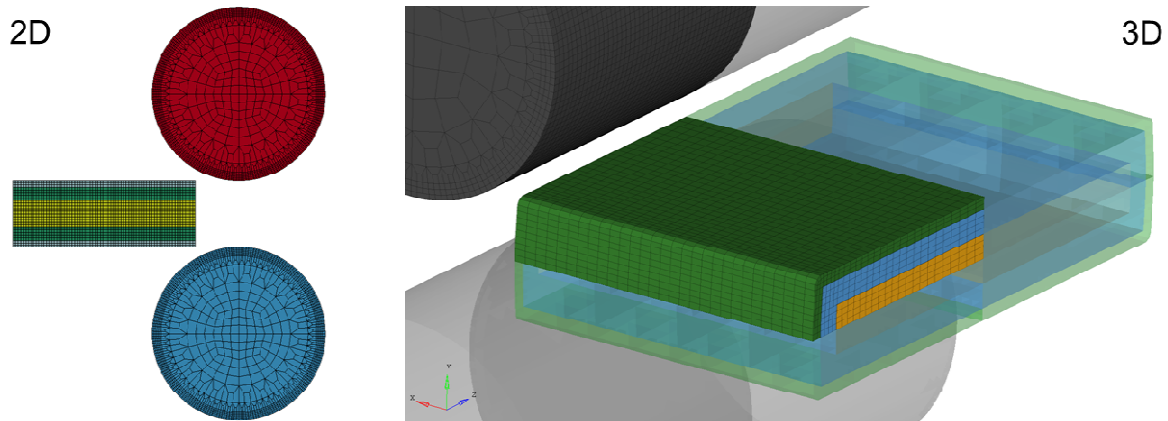
Fig.2: Used 2D plane strain shell mesh (left) and 3D solid mesh (right) for hot rolling simulation

A heat exchange between billet and environment is considered by the outer billet surfaces whereas the ends in rolling direction are excluded. For simplification a combined heat transfer coefficient of convection and radiation effects is used which is recommended by Shapiro [6]. The necessary segment set for ***BOUNDARY_CONVECTION_SET** is defined for the solid mesh by using ***SET_SEGMENT_GENERAL** where segments from the outer billet part are excluded by several ***DEFINITION_BOX** keywords. Because the usage of ***SET_2D_SEGMENT** showed some irregularities regarding the temperature distribution a python routine was provided, which reads the nodal coordinates of the mesh file and defines segments of the billet top and bottom surface by nodes separately. A general heat transfer coefficient range is given in Table 1 for hot rolling simulation. Initial temperatures were set for rolls and billet according to the user input within the GUI.

	Coefficient	Value	Unit
Contact	fs	0.2 .. 0.6	-
	htc	8.0 .. 15.0	kW/m²K
	cf	0.2 .. 0.5	W/mK
Billet	hc	850.0 .. 1150.0	J/kgK
	tc	120.0 .. 160.0	W/mK
Env.	htc	15.0 .. 75.0	W/m²K
	$T_{ambient}$	25 .. 55	°C

Table 1: Typically used friction and thermal coefficients for hot rolling simulation

The implicit time integration method needs some additional keywords within LS-Dyna:

```
*CONTROL_IMPLICIT_GENERAL
*CONTROL_IMPLICIT_SOLUTION
*CONTROL_IMPLICIT_AUTO
*CONTROL_IMPLICIT_DYNAMICS
```

Recommendations by Erhart [7] and Borrvall [8] were adopted for the implicit solver setup. The initial mechanical time step was set to 1.0 ms for the rolling simulation and to 50.0 ms for the thermal simulation. An automatic time step control was activated, allowing a time step size between 0.001 and 5.0 ms for the rolling step and a time step size between 1.0 and 500.0 ms for the thermal step. The mechanical time steps varies between 0.7 and 2.0 ms for the rolling simulation and for the thermal simulation around 320 ms during multi pass hot rolling simulation.

2.3   Introduced trimming routine

Figure 3 shows exemplary an assumed rolling process without virtual trimming for n passes using an initial billet length of 1.0 m at the first pass. It is evident that with each pass the billet length to simulate increases. Thereby the process time increases and hence the computational time increases as well to an unacceptable level.
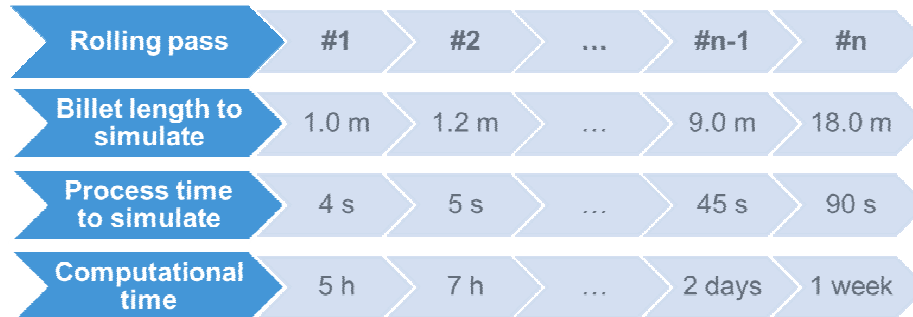
Rolling pass	#1	#2	…	#n-1	#n
Billet length to simulate	1.0 m	1.2 m	…	9.0 m	18.0 m
Process time to simulate	4 s	5 s	…	45 s	90 s
Computational time	5 h	7 h	…	2 days	1 week

Fig.3:   Evolution of billet length, process and computational time without trimming during multi pass hot rolling

To keep the computational time at an adequate level the original billet length of more than 6.0 m has to be kept constant at 1.0 m. Because the billet edge deformation is unknown apriori before rolling it is not possible to create just a new mesh and map the forming history from previous simulation to the new model. A re-meshing is needed to avoid strong element distortions and bad aspect ratios. A python based trimming routine was developed in order to overcome these issues. The developed routine for 3D simulation is shown as a graphical overview in Figure 4 and obeys the following scheme:

1. Extraction of the billet from the complete model dynain file of the previous rolling simulation into a separate keyword file.
2. A python subroutine reads the nodal coordinates of the billet mesh and calculates the billet center with respect to rolling direction
3. A LS-PrePost command is created by a second python subroutine, which extracts a cross section cut at the previous determined mid of the billet and writes a general model checking summary of the 2D cross section cut mesh. The general model checking summary contains information about the element quality and how many quads or trias elements are present in the mesh. A python subroutine reads the general model checking summary and checks if the cross section cut mesh contains some trias elements. If there are trias elements present, a new LS-PrePost command is generated with a different cross section cut position along rolling direction. The cutting position is changed iteratively until no trias elements are present.
4. If no trias elements are present in the cross section cut mesh, the 2D mesh is extruded to 1.0 m billet length. So a new mesh including the deformed edge shape is generated.
5. An element row containing all element results including history variables is extracted at the cross section cut position.
6. The element results of the element row are now mapped to the previous generated "result free" solid mesh using LS-PrePost.
7. A last python subroutine collects the nodal coordinates of the extracted element row and corresponding node number. The node number is necessary to find the relevant temperature within the new_temp_ic.inc file, which contains temperatures per node. Hence the temperature at each node position is known and could be transferred to the nodes of the new billet mesh.
8. New mesh file with element results including all history variables and a new temperature file are provided for the next rolling pass.
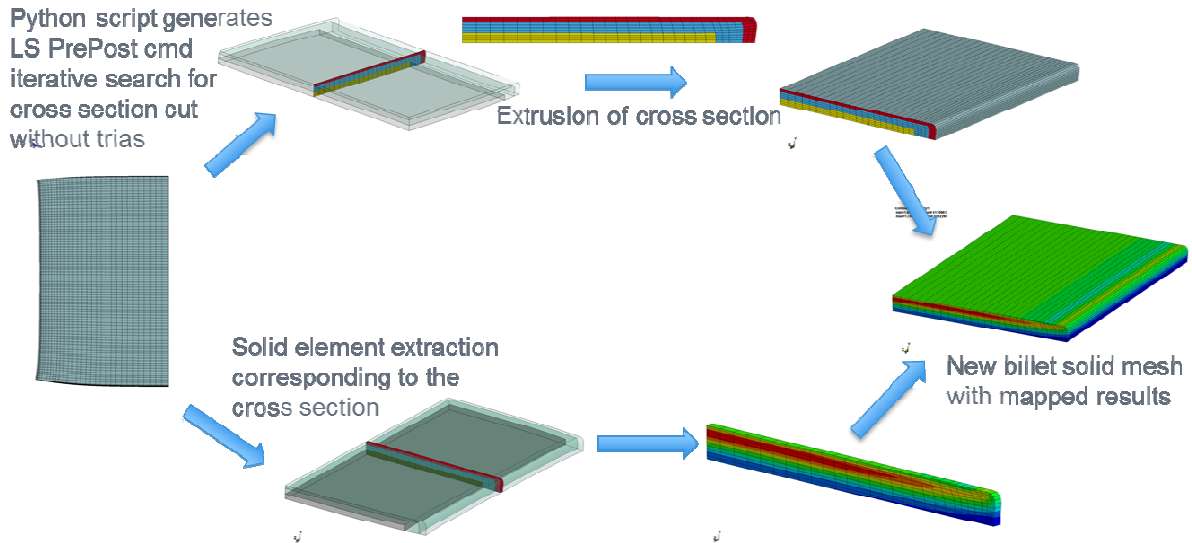
Fig.4: Schematic trimming routine of the billet for 3D shot rolling simulation

For 2D simulation it is much easier to trim the billet to the length of 1.0 m, because the billet edge is neglected. The element strip in the center of the billet is used for element result output. The shell element strip is extracted by using the elements given in the elout file. A new billet mesh with the height of the minimal and maximal coordinate in height direction of this strip is generated. The forming results and temperatures of the extracted shell strip are mapped to the newly generated mesh as in the case of the 3D simulation. With the trimming methods it is possible to keep the billet length constant at 1.0 m for 2D and 3D simulations. A correct transfer of the simulation results from one rolling pass to the next is guaranteed. Figure 5 shows a comparison of the equivalent plastic strain before and after the trimming operation. It is evident that no crucial difference could be found, if the billet end effects are neglected.
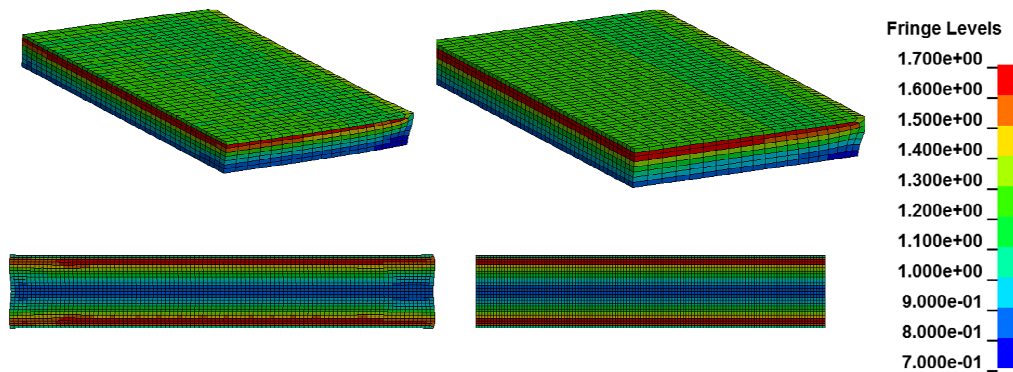

Fig.5: Comparison of equivalent plastic strain before (left) and after (right) trimming for 2D simulation (below) and 3D simulation (above)

3 Results

3.1 Comparison explicit versus implicit time integration

The project to develop an internal rolling simulation strategy at AMAG rolling GmbH started in mid 2013 using the explicit time integration method of LS-Dyna. It was not possible to use the implicit time integration method for the rolling stage at this time, due to convergence and contact problems, which could not be solved. Since release R9 of LS-Dyna these problems were solved and the implicit time integration scheme can be used. Figure 6 on the left side shows the computational time of a 3D solid

simulation of the pass plan for 7xxx series aluminium alloy plates with 9 passes. The blue colour indicates the rolling step and the orange colour the thermal step of each pass. The thermal simulation is conducted always with the implicit time integration scheme. The thermal stage at pass 7 takes much longer, because a break of a few minutes for trimming in the real rolling process is included. To reduce the computational time the billet initial billet length of 1.0 m was set to 0.75m for the last pass. When the billet is thinner it is possible to reduce the virtual billet length without consequences for the relevant part in the middle of the billet. The computational time for each pass is summed up and is shown in Figure 6 on the right side for comparison of 2D and 3D implicit and explicit hot rolling simulation. The simulations were performed on a Windows 7 64 bit workstation with two Intel Xeon E5-2680 @ 2.7 GHz using 4 CPUs. It is evident that by using the implicit time integration of LS-Dyna the computational time could be reduced dramatically. For the 2D simulation the implicit solution is around 6.5 times faster and for the 3D 2.5 times faster compared to the explicit solution. Especially with the 2D model the computational time is short enough to allow Design of Experiments or optimization studies using for example LS-Opt. Number of nodes and elements during hot rolling simulation are given in Table 2. Of the total number of elements 3576 shell elements and 5680 solid elements are rigid for the 2D and the 3D simulation respectively. The number of nodes and elements increases slightly due to the fact that the mesh density in rolling direction decreases after each pass depending on the element length along the billet height. For the 9th pass the number decreases a bit due to the shorter virtual billet length of 0.75 m.
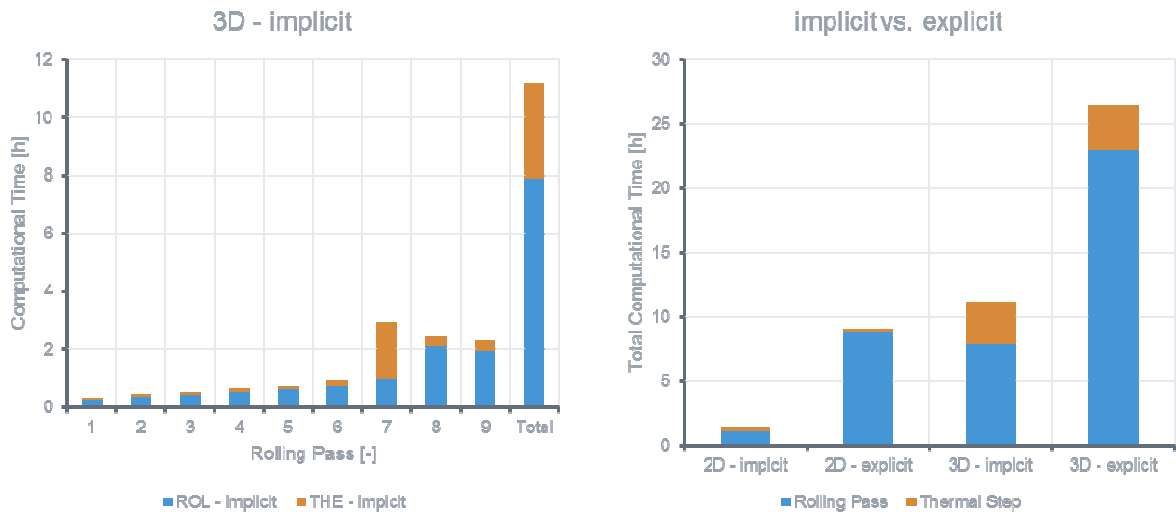

Fig.6: *Computational time per pass for a 3D implicit simulation (left) and comparison of the total computational time for 2D and 3D implicit and explicit hot rolling simulation (right).*

Pass	2D		3D	
Number	Nodes	Shells	Nodes	Solids
1	5360	5058	11603	9655
2	5468	5162	11603	9655
3	5630	5318	11977	9973
4	5846	5526	12725	10609
5	6116	5786	13473	11245
6	6548	6202	14595	12199
7	7142	6774	16091	13471
8	8060	7658	18709	15697
9	8330	7918	16465	13789

Table 2: Number of nodes and elements for each pass

3.2 Comparison of simulation and real measurements

In order to perform variation studies and to find new rolling strategies a validated simulation model is necessary. The rolling force and the temperature are two reasonable characteristic values for hot rolling. Figure 7 exemplarily shows both force versus time and temperature versus time a single pass after several hot rolling passes. Two element positions are used for investigation. Both positions are located in the mid of the billet length, one at the surface and one at the core of the billet. For both positions it is evident that the temperature is almost constant until the rolling gap is reached. Due to the contact with the cold rolls the temperature decreases fast for the surface position whereas the core temperature increases a bit due to plastic work. Outside the rolling gap, the surface heats up again until the surface convection becomes a stronger effect than the internal heat up. For the comparison with the real measurements the average temperature value of the billet surface position during the thermal step is used. For comparing the rolling force the contact force provided by the `*DATABASE_RCFORC` keyword is used. A contact definition is only active for the rolling stage. A mean force value is calculated between initial force peak and end force peak. This mean value is used afterwards for comparison with the real measurements.
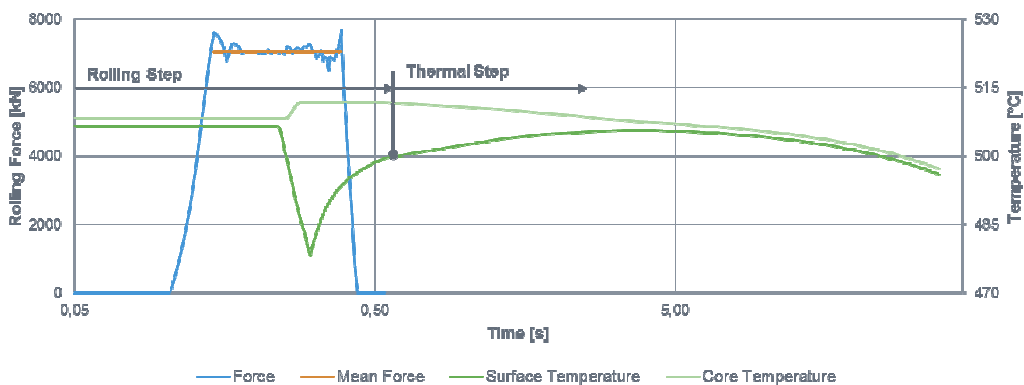

Fig.7:   Characteristic evolution of force and temperature during a single hot rolling pass

For the 2D simulation a good agreement between measured and calculated rolling force was obtained as shown in Figure 8.The difference amounts to less than 5 % of the measured forces. In contrast to this, the 3D simulation overestimates the rolling force a bit and does not have the force drop at pass 10. The reason is not clear so far and needs more detailed investigations. The force prediction of 3D simulation is still acceptable, because the differences are not more than 10 %. In the industrial process the temperature is measured with a pyrometer which is located at some distance from the rolling gap. For the first passes the billet length is so short, that the position of the pyrometer is not reached. When the billet reaches the pyrometer the measurement of the surface temperature starts. The measurement is influenced by surface effects of the billet, for example the rolling emulsion on the surface. Therefore the measured temperature should be considered with care as estimates and not as exact values. Nevertheless the simulation results for both models show an acceptable agreement of the surface temperature.
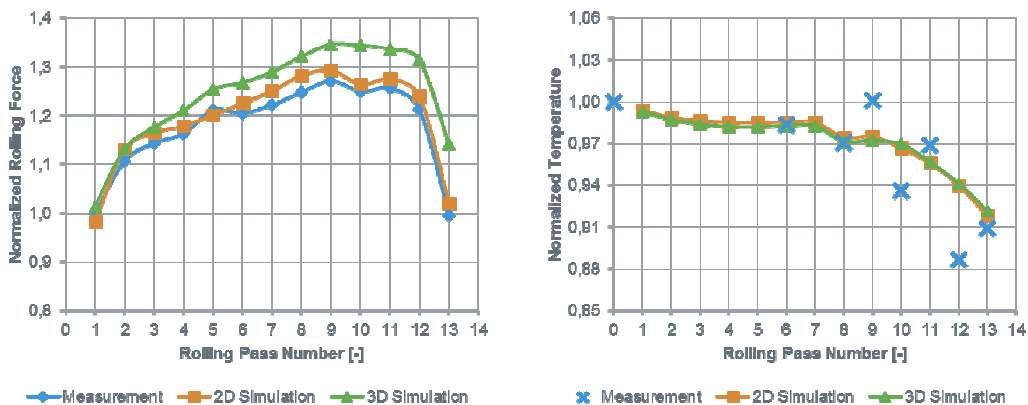

Fig.8:   Comparison of measured and calculated rolling force (left) and surface temperature (right)

3.3 Billet Edge Deformation

For 5xxx series aluminium alloys the edge deformation is of interest, because edge cracks can occur at high deformations. These cracks are not relevant for product properties but can cause problems during the production phase, especially during edge trimming. The edge deformation mainly depends on edge shape, billet format and rolling regime. For a detailed investigation of the edge deformation hot rolling simulation was used. The edge deformation obtained by rolling simulation for each pass of a 5xxx series aluminium alloy industrial pass plan is shown in Figure 10. For a better visibility the billet edge in the picture is moved to the right side for each pass. The high deformation of the billet during hot rolling from the first pass to the final pass is apparent. It is impressive how high the deformation degree from the initial thickness to the final thickness is.

Fig.9: *Real billet edge cracks (right) and calculated edge deformation (left) of 5xxx series aluminium alloy after hot rolling at the new hot rolling mill using bigger billet dimensions*

A comparison of the real and the simulated edge shape is shown in Figure 10. The agreement is good. The billet edge shape was modified according to production experience to suppress the edge crack effect successfully. The simulation should help to optimize the edge shape and the rolling strategy in detail. Therefore a damage model for edge cracks according to was implemented in the LS-Dyna user defined material model. Rolling simulations with the initial and the modified edge shape were conducted. A comparison of both shapes regarding the obtained damage value is shown in Figure 10. Similar to the real rolling process a change of the initial edge shape strongly decreases the crack affinity. Furthermore the deformation of the edge is not that much pronounced for the modified shape compared to the initial edge shape.
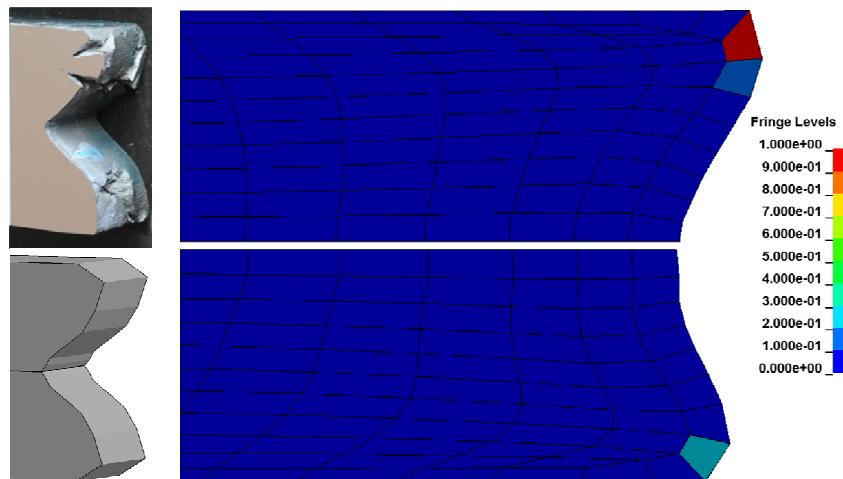

Fig.10: *Comparison of real (left top) and calculated edge shape (left bottom) including damage prediction for initial (right top) and modified (right bottom) edge shape*

3.4 Homogeneous strain gradient along billet thickness

One special requirement of thick aluminium plates is a homogenous grain size distribution along the thickness direction. Due to the fact that the grain size is determined by different effects as for example temperature, initial microstructure and strain simulations were conducted to improve the homogeneity along plate thickness. Therefore the plastic strain distribution was chosen to be optimized by modifying the pass plan. The optimisation was performed manually by analysing the effective plastic strain along a node path in the billet center as shown in Figure 12. The optimised pass plan just show a small improvement regarding the strain gradient along billet thickness. The difference between maximal and minimal strain amounts 0.64 compared with the initial pass plan where a difference of 0.69 was achieved. The initial or standard pass plan could be seen as an optimum regarding the requirements given by the production. A difference of about 0.9 between the maximal and minimal strain was achieved for a worst case pass plan. It is evident that the strain value close to the surface can be influenced by the chosen pass plan strategy.
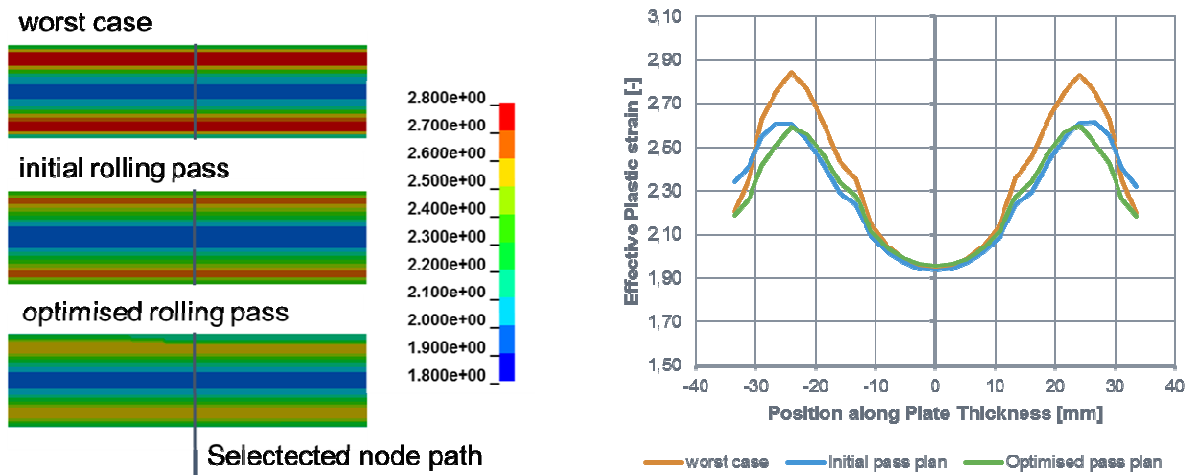

Fig.11: Comparison of the effective plastic strain distribution of the billet (left) and along the billet thickness (right)

4 Summary and Outlook

In this work a hot rolling simulation method using LS-Dyna was presented. In order to reduce the model preparation time a fully automatic simulation setup was developed. Therefore several python routines are used to generate command file for LS-PrePost (i.e. mesh generation, result mapping). A python and LS-PrePost based trimming method of the billet was described. This trimming method allows to keep the length of the simulated billet fraction constant to reduce the computational time. Moreover a comparison of the explicit with the implicit time integration method was presented. The implicit solver allows a 6.5 times faster simulation for the 2D case and a 2.5 times faster simulation of the 3D case for an industrial hot rolling pass plan. The hot rolling simulation showed a good agreement compared to results obtained by industrial rolling passes. Besides rolling force and rolling temperature the billet edge deformation was good predicted in the simulation.

The described hot rolling simulation method will be further developed and used to conduct variation studies of the pass plan and to establish a best possible hot rolling strategy without costly real world trials. An extension of the simulation regarding additional production processes subsequent to hot rolling are planned.

5 Literature

[1] Hirsch, J.: "Virtual fabrication of aluminium alloys", Wiley-VCH Weinheim, 2006.

[2] Mecking, H.; Kocks, U.F.: "Kinetics of flow and strain hardening", Acta Materialia, 29, 1981, 1865-1875.

[3] Sherstnev, P.; Melzer, C.; Sommitsch, C.: "Prediction of precipitation kinetics during homogenization and microstructure evolution during and after hot rolling of AA5083", International Journal of Mechanical Sciences, 54, 2012, 12-19.

[4] Leblond, J.; Perrin, G.; Suquet, P.: „Exact results and approximate models for porous viscoplastic solids", International Journal of Plasticity, 10, 1994, 213-235.

[5] Riedel, H.; Andrieux, F.; Walde, T.; Karhausen, K.-F.; "The Formation of Edge Cracks during Rolling of Metal Sheet", Steel Research International, 78, 2007, 818-824.

[6] Shapiro, A.B.: "Using LS-Dyna for Hot Stamping", 7th European LS-Dyna Conference, 2009

[7] Erhart, T.: "Webinar LS-Dyna Implicit", Dynamore GmbH webinar presentation, Feb. 2015

[8] Borrvall, T.: "A Guide to Solving Implicite Mortar Problems in LS-Dyna", www.lsdynasupport.com, Implicit Guidelines, Feb. 2017