Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 81 (2014) 18 – 27

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan

Selected processes and modeling techniques for rolled products

G. Hirt, S. Senge*

Institute of Metal Forming, RWTH Aachen University, Intzestraße 10, Aachen 52056, Germany

Abstract

The majority of all metals will undergo a rolling process during the production chain from metal generation to the final product. These rolling processes may be used to define the product geometry, the material properties or functional surface properties. The paper reviews selected processes for tailor rolled products as well as modeling techniques helping to design or optimize these processes. Their common goal is to improve material efficiency in flat rolling and in application of rolled products.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Light weight design; Tailored thickness distribution; Metal forming; Closed loop feedback control; Roll bonding; FEM; Surface structure

1. Introduction

As the majority of all metal produced undergoes a rolling process an enhancement of rolling efficiency can deliver significant contribution to sustainability. Driving forces for rolling process development originate from the need to improve energy and material efficiency which is often in line with reducing costs. Other drivers are the increase of the product value, i.e. defined by geometric properties or material properties which permit final products with improved performance during their usage. These development trends will be exemplarily reviewed with respect to (1) light weight design by tailor rolled semi-finished products, (2) increasing the functionality of rolled products by tailoring the properties across the thickness by the roll bonding process, (3) tailoring surface properties and by (4) improvement of process layout by modeling and simulation on various scales.

---

* Corresponding author. Tel.: +49 241 80 95945; fax: +49 241 80 92234.
E-mail address: senge@ibf.rwth-aachen.de

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University
doi:10.1016/j.proeng.2014.09.124

2. Rolling and casting processes for tailored cross sections

With regard to flat rolled products material efficiency includes to create the desired thickness distribution already during the rolling process. Today processes like “flexible rolling” or “strip profile rolling” allow light weight design by an efficient production of thin sheets or strips with a defined thickness variation in the longitudinal or width direction. Newer approaches are direct casting of thin strips with a thickness variation in the width direction by using the vertical double roller strip casting process and rolling of axially profiled rings.

2.1. Thickness distribution in length direction

Flexible rolling is a modified cold rolling process, which allows large-scale production of sheets with variable thickness in the longitudinal direction [1, 2]. The so called Tailor Rolled Blanks (TRB) are produced by a closed loop controlled modification of the roll gap during the flat rolling process ensuring that the predefined thickness distribution is achieved within tight tolerances. The thickness variations are desired to obtain a load-optimized wall thickness distribution in structural components, i.e. parts for automotive applications.

Nowadays, flexible rolling is a state-of-the-art technology to produce load-optimized lightweight structure parts. For example Mubea produces up to 300.000 tons per year at the production sites in Attendorn, Weißensee (Germany) and Florence (USA). The TRBs are used as starting material for a large variety of parts in the automotive industry (e.g. bumpers, pillars, chassis subframe) and load-optimized pipes. Up to now, the TRBs are mostly made of various steels from deep drawing steels up to advanced high strength steels (AHSS).

2.2. Thickness distribution in width direction

The process of strip profile rolling is characterized by the use of narrow profiled rolls which facilitate a transversal material flow (spreading) and thereby permit the production of a profile in width direction. Kopp [3] explains the mechanism of the lateral material flow using the ratio of contact-width to contact-length. If the ratio is significantly smaller than 1.0 the lateral material flow dominates in the process. According to Utsunomiya [4] and Abo-Elkhier [5] the geometric parameters of the profile rolls (diameter, width, etc.) also influence the spreading ability during the rolling process.

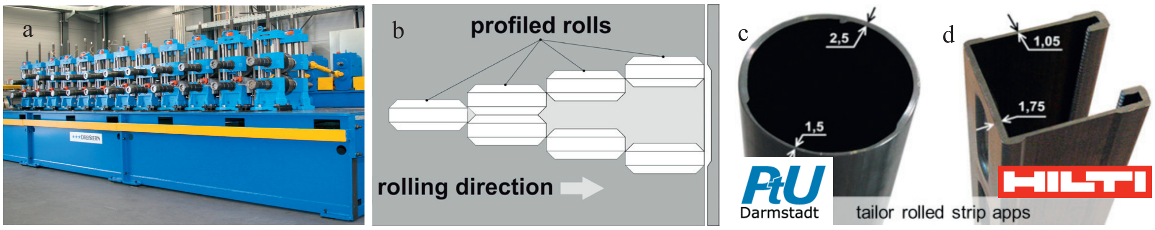

Fig. 1. Strip profile rolling mill (a), rolling strategy (b), demonstrator profile (c) and commercial profile (d) made from Tailor Rolled Strips.

Spreading is necessary to prevent a material flow in longitudinal direction, which would result in buckling of the strip [6]. In order to produce wider grooves several subsequent rolling passes with a symmetrical roller setup can be used (Figure 1). For example a 12-stand strip profile rolling mill has been successfully used to produce Tailor Rolled Strips (TRS) by the above mentioned rolling strategy with several subsequent passes. Further manufacturing, i.e. by roll forming and welding processes, leads to load-optimized structural profiles (Fig. 1c and d) [7].

The process discussed afore is based on a larger number of rolling passes using conventional sheet material as a starting product. Ferry [8] described the strip casting process using the twin-roller procedure. In this process thin strips are produced directly from the melt which is poured between counter-rotating casting rollers, where it solidifies into a strip in a continuous process. If in the course of strip casting it were also possible to produce strips with a defined thickness profile across the strip in a single stage, then this would offer a considerable shortening of the process chain. Recent research deploying numerical simulations and experimental investigations demonstrates the basic feasibility of profiled steel strip being produced by means of thin-strip casting [9].

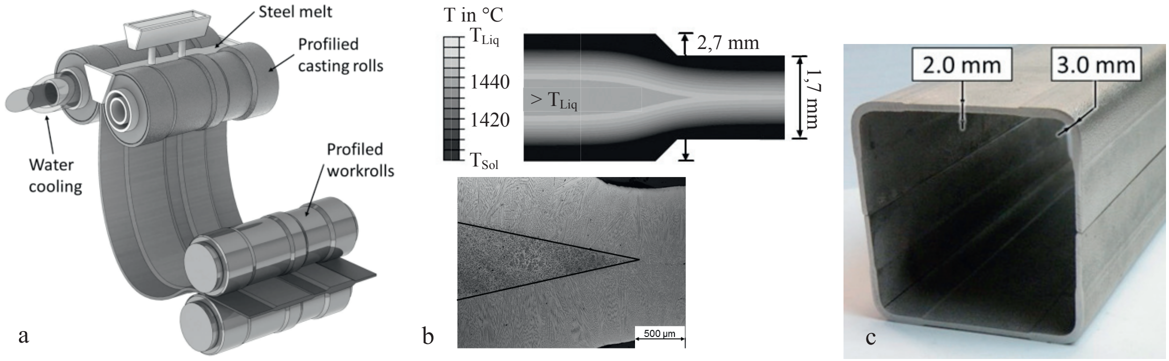

Fig. 2. Schematic view of the profile strip casting process (a), the dendritic crystallization and the temperature profile (b) and produced profiles (c).

2.3. Profiles with longitudinal variation of the cross section

Carruth and Allwood (2011) proposed a hot rolling process for the production of I-beams with a variable cross-section. Figure 3 shows the key forming stages and the necessary roll geometry. It is foreseen to produce an I-beam with a bulge in the middle. In the last step of the process this bulge will be rolled out, so that the beam spreads. The process was investigated in FEM simulations and rolling experiments with plasticine. Both, the simulations and the experiments showed that the process is feasible whilst some restricting parameters, e.g. the bulge area ratio, are not exceeded [10].

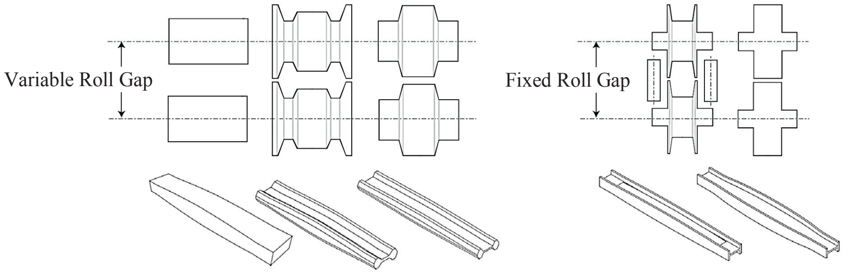

Fig. 3. Forming stages of the variable cross-section beam process and workpiece geometries after each stage [10].

2.4. Rolling of axially profiled rings

Ring rolling is used to manufacture a wide geometrical range of seamless annular components from different materials on a single machine. In order to reduce the loss of material and the subsequent machining rolling of axially profiled rings is an interesting process development. However, due to the continuously changing ring geometry, modified control strategies are required to avoid rolling defects. Accordingly for a realistic simulation the closed-loop structure from the real process has been implemented within the FE environment consisting of virtual sensors and actuators to allow for virtual testing of new self-designed control algorithms (see Fig. 4). Furthermore, with the information gained from the simulations, experiments were successfully carried out [11].

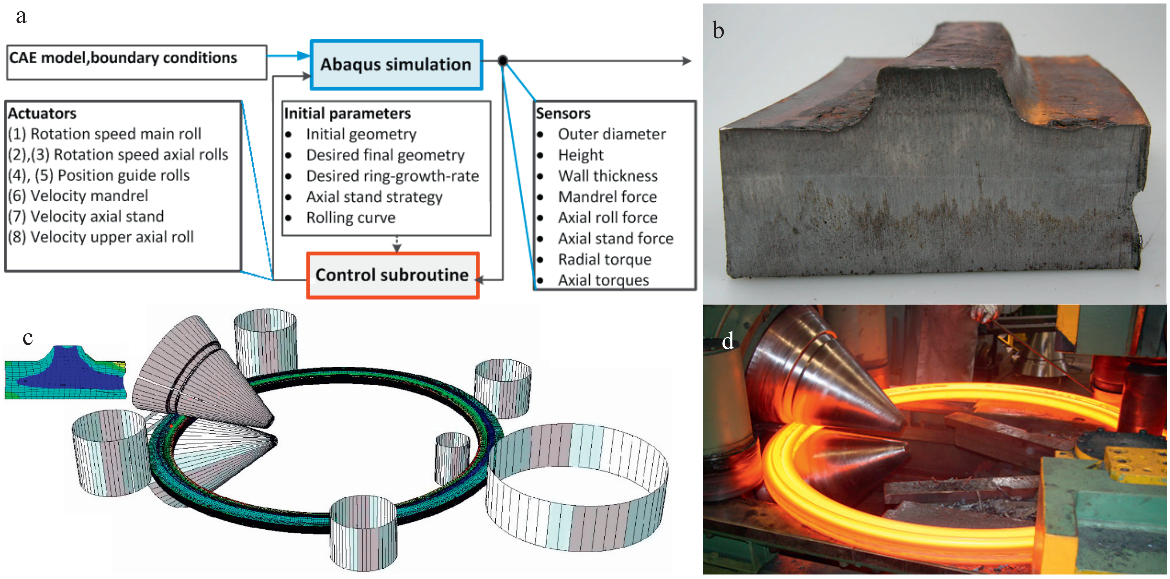

Fig. 4. Closed loop control for ring rolling simulation (a), achieved product (b), axially profiling of rings in simulations (c) and in reality (d).

The results show that using this control strategy rings with axially profiled cross section can be rolled on slightly modified radial axial ring rolling machines. However the development of the process strategy still requires at least numerical trial and error procedures, which might in future eventually be avoided by including additional sensors in the process which monitor the profile evolution [12].

3. Tailored properties across the thickness

Tailored properties across the thickness of strips and sheet can be achieved by roll bonding processes, which however become difficult if metals of significantly different strengths shall be combined. In such cases there is the trend that the softer material elongates more than the harder material. This may lead to failure of the initially weak bond and subsequently to inacceptable excess length of the softer plating as shown in Fig. 5a in a simplified laboratory test.

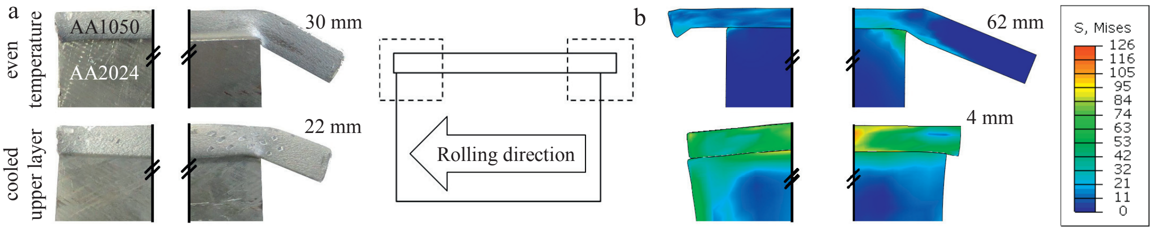

Fig. 5. Different layer-elongation in the experiment (a) and finite element simulation (b) .

For the upper figure both partners (AA 1050 as upper and AA 2024 as lower layer) were heated to 470 °C while for the lower figure the softer upper layer was cooled to achieve a similar flow stress during rolling [13]. This method obviously has reduced the excess length but could not completely avoid it. In a preliminary FE simulation, in which the layers were just combined by a relatively large friction factor, the tendency of reducing the excess length is significantly overestimated (Fig. 5b). Accordingly a better Finite Element framework is currently being developed [14].

This enhanced numerical model shall be able to predict bond creation and bonding strength based on material characteristics and local parameters of the contact surface. Therefore the ABAQUS User subroutine "UINTER" was used to compute the normal and tangential strength of the bond as a function of the local parameters and allowing tangential sliding and separation if this strength is exceeded. The bond strength was initially calculated following Bay's model [15, 16]. Then this value is compared to the local loading stresses and depending on the comparison the bond is either maintained or released [14]. Comparisons with results of Zhang and Bay showed that the bonding strength, calculated by the subroutine is similar to those of Zhang and Bay [15, 16].

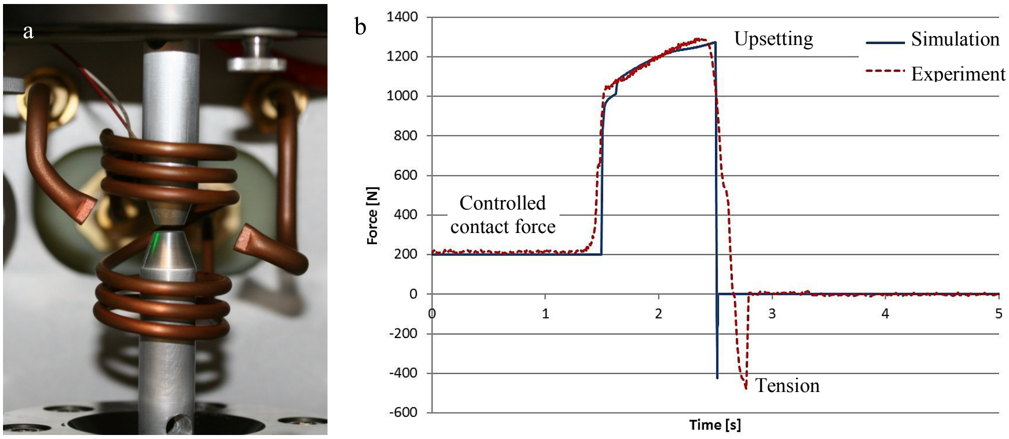

Fig. 6. Experimental setup (a) and comparison of experimental and simulative force measurements (b) [17]

However in order to be able to include further influencing parameters, like temperature or surface condition into the model a combined compression and torsion test was developed, which allows to vary the parameters influencing the bond formation (surface enlargement, temperature, tangential sliding,…) as well as direct subsequent testing of the bond strength by tension and/or torsion. A typical test history (red line) as well as the result of a simulation of the test utilizing an empirical bond strength function derived from a test series is shown in Fig. 6b. The simulated tensile strength is in a good agreement with the experimental data [17].

4. Tailored surface properties

Tailored surface properties are commonly defined by skin pass rolling. They determine tribological, optical or other properties of the surface. Recently it could be shown that also cladded high strength aluminum alloys that are used in aerospace applications, can be structured with very fine riblet surfaces which reduce friction drag. This plastic deformation additionally hardens the surface, making it less liable to fatigue [18]. As the tip radius of the riblet should be as small as possible, preferably in the range of less than 1 μm, machining the negative imprint into the roll surface is very difficult. Therefore a wire winding process is used to realize structured roll surfaces by the continuous attachment of round steel wire on the flat roll surface. Riblet spacing can be chosen according to available steel wire diameters, radii at the riblet tips are converging to zero [19].

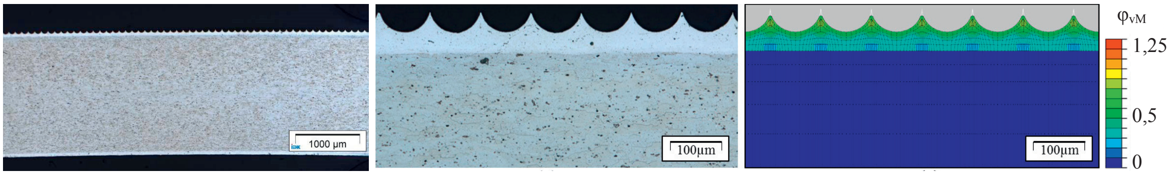

Fig. 7. Produced riblet surface on cladded AA2024-T351 strip and the according simulation [20].

5. Computational modeling of the flat rolling process chain

5.1. Overview of rolling process modeling

Computational modeling of the flat rolling process chain is performed with different objectives in focus, for instance the prediction or improvement of (1) force, torque, temperature for roll pass design, (2) microstructure and material properties during and after rolling, (3) metal flow and surface structures, (4) sheet profile, roll flattening, roll wear and rolling defects.

According to this large variety of simulation objectives, numerous different models are employed in the industrial and academic field [21]. Especially the global target values, like forces or torques, can effectively be described with relatively simple models based on the slab theory by von Karman [22], which may be combined with simplified models for temperature prediction [23]. The coupling between tandem mills is well taken into account on this level in industrial praxis [24]. In addition, various analytical models exist for the inclusion of roll flattening and deflection [25]. While these models are generally fast enough to allow their use for automatic optimization or online application in control systems, the increasingly powerful numerical FE models, still require large computational times, but enable to achieve a high resolution of results on all scales; from microstructure, as shown by Roters [26] and Helm [27] to machine behaviour discussed by Brecher [28]. Specifically in ring rolling the integration of the control algorithms in the FE analysis is vital [29].

5.2. Fast models for pass schedules in plate rolling

From an industrial point of view the main objective for modeling of rolling processes is the prediction of the roll force, torque and the microstructural events during the rolling process. For the prediction of roll force in plate rolling, fast analytical models, based on the slab method are still considered the industrial standard today [30]. Closed form solutions to calculate the force according to Siebel and Lugovskoi are presented in Fig. 8. They differ in the calculation of the geometry factor Q_P. The geometrical parameters in the equations are b_m for the mean width, l_d for the contact length and h_m for the mean height whereas k_f represents the flow stress.

Siebel:

$$F = b_m \cdot l_d \cdot k_f \cdot \underbrace{\left(1+\frac{1}{2}\mu\frac{l_d}{h_m}\right)}_{Q_P}$$

Lugovskoi:

$$F = b_m \cdot l_d \cdot k_f \cdot \underbrace{\left(1{,}25\frac{l_d}{h_m}+1{,}25\ln\left(\frac{h_m}{l_d}\right)\right)}_{Q_P}$$

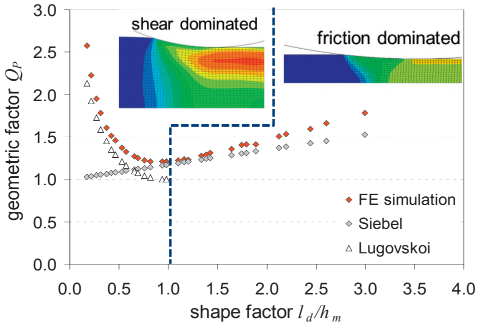

Fig. 8. Solutions of the slab method according to Siebel and Lugovskoi.

While the model calculations for force and also torque are commonly based on average values for the sake of speed, robustness and adaption, the calculations of grain size distribution over the plate thickness demand for local values for strain, strain rate and temperature. The temperature field can effectively be solved by FDM algorithms on a local discretised grid. The same grid can also be applied to map the values of local strain and strain rate in the roll gap by means of empirical analytical functions with respect to the geometric conditions in the roll gap. The equivalent strain ε_{eq} then is defined according to von Mises including the local shear distribution (Fig. 9), which has been calibrated by means of a FE parameter study, for a wide range of plate thickness and pass reductions [31]. With 50 parameter combinations of the initial height h_0=5-900 mm and pass reductions between ε_h=1-30% the entire range of plate rolling parameters, including the rolling of ultra-heavy blocks is covered. Keeping the roll radius fixed at R=550 mm and the friction factor at μ=0.35, common values for plate rolling configurations are assumed.

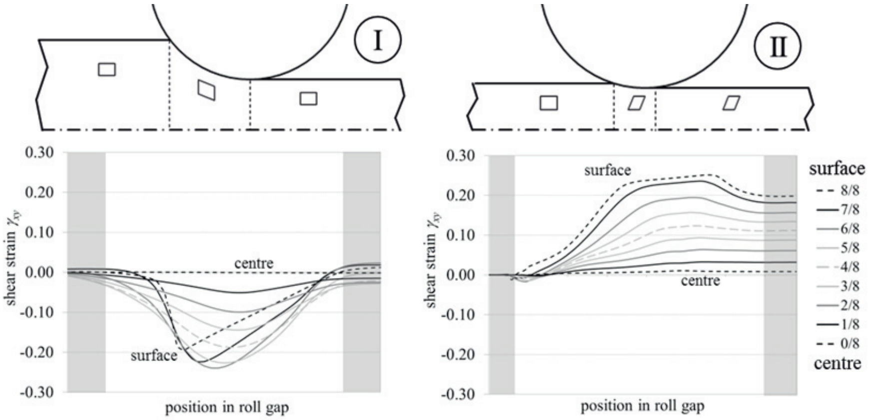

Fig. 9. Grid distortion and net shear strain through the roll gap for thick plate (h_0=400mm; Δ_h=20%; l_d/h_m=0.57) and thin plate (h_0=10mm; Δ_h=20%; l_d/h_m=3.68).

Using the local shear strain to determine the equivalent plastic strain as shown in Fig. 10 gives two typical shapes of the strain distribution over plate thickness due to the influence of outer friction and inner friction.

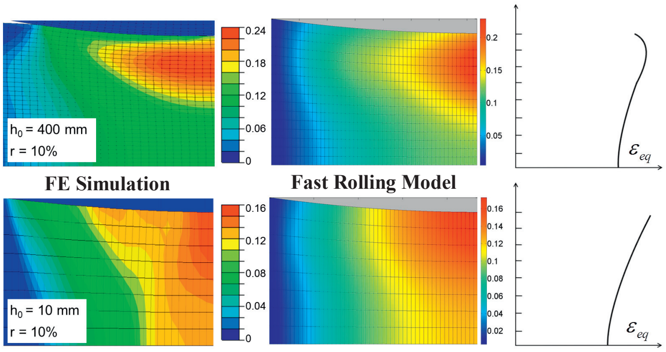

Fig. 10.Distribution of strain components in the roll gap and the resulting equivalent strain according to the developed shear strain model (h_0 = 10 mm; ε = 20 %).

In fast rolling models the kinetics of recrystallization and the grain size evolution are commonly described by a set of empirical formulations, i.e. according to Sellars et al. [32-34]. Furthermore they are based on input, which defines the process and material parameters, such as thermal material properties, roll parameters, flow stress parameters, recrystallization parameters, grain-growth parameters, pass schedule. Typical results include force, torque, temperature distribution, recrystallized fraction, grain size, some of which are displayed in Figure 11 for a typical plate rolling case calculated by a self-developed simulation tool named RoCaT (Rolling Calculation Tool).

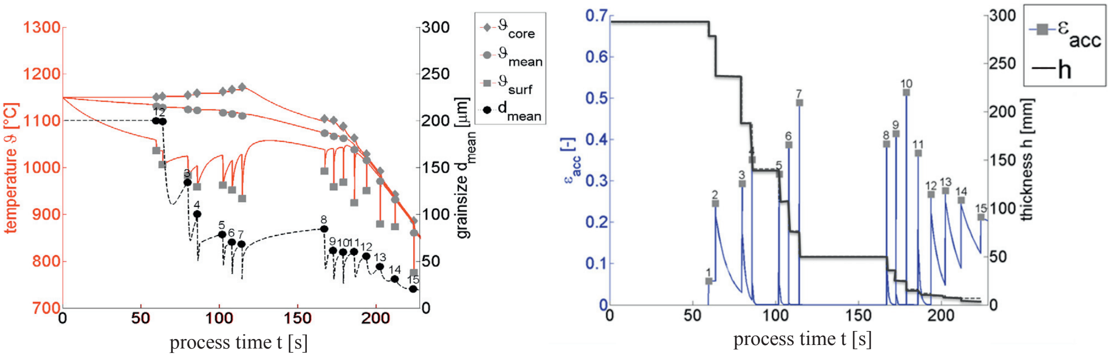

Fig. 11. Results of the RoCaT model for the rolling schedule of a C-Mn steel plate.

Slab method based rolling models can give a solution within seconds of calculation time and thus can be used for inverse modeling and optimization. As an example an inverse technique was developed to improve the prediction quality of such models. Force values for multiple slabs obtained from the former mentioned rolling model are passed to a cost function in conjunction with the forces measured during industrial rolling. This cost function (Eq. (1)) is used to evaluate the level of agreement between measured and calculated forces in a least square sense. Then the parameters of the material model embedded into the rolling model are adjusted to achieve a better mean flow stress prediction and hence a rolling force prediction closer to the measurement. Over several iteration steps the cost function value finally reaches a minimum, where the material model parameters are optimal. A flow diagram of this inverse concept is illustrated in Figure 12a.

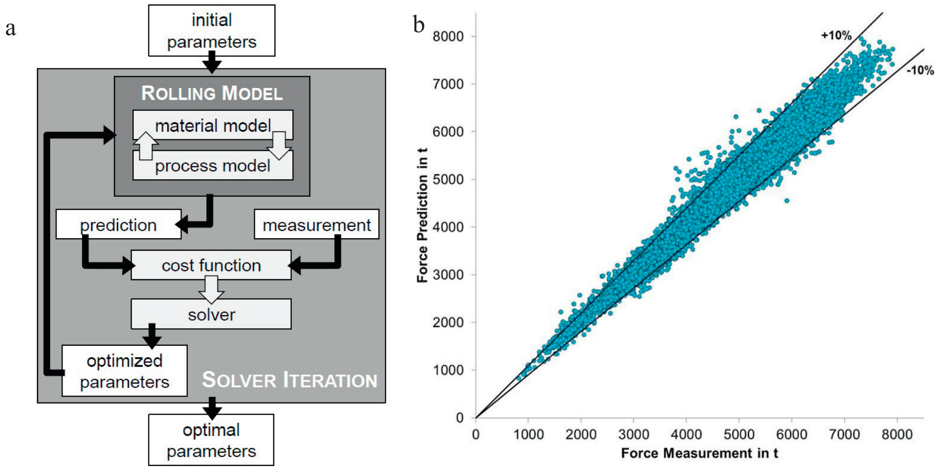

Fig. 12. Inverse modelling concept (a) and comparison of measurement and prediction (b).

The mathematical definition of this nonlinear optimization problem is given in Eqs. (1) and (2) where θ is the vector of all parameters, index i represents the slabs and index j represents the individual rolling passes.

$$J(\theta) = \sum_i \sum_j \left(F_{ij}^{(measurement)} - F_{ij}^{(calc)}\big(\sigma(\theta)\big) \right)^2 \quad , \tag{1}$$

$$\theta_{opt} = \arg\min J(\theta) \quad , \tag{2}$$

The results discussed hereafter were all generated during an optimization run consisting of ~50 iterations and involving 4.000 industrially rolled slabs with in total ~88.000 passes. A comparison between the measured forces and the corresponding predictions with optimal material model parameters for all the rolling passes is shown in Fig. 12b. It is visible from the plot that the general level of agreement is good with most predictions within a 10% range of the measurement. Additionally the number of outliners with deviations of more than 20% is considerably small [35, 36].

6. Conclusions

At least the following conclusions may be drawn from the previous sections:

(1) Modified rolling processes allow the production of strips with tailored properties such as defined thickness distributions (i.e. flexible rolling, strip profile rolling, profile strip casting), material combinations (i.e. roll bonding) or functionalized surfaces (i.e. riblet rolling) thus providing additional product value. Some of these processes were primarily designed for specific metals or specific applications but their transfer to other metals or other applications might open new opportunities.

(2) For many industrial optimization tasks fast numerical models based on the slab theory including some enhancements for the distribution of temperature and shear across the thickness (RoCaT) may effectively be used in combination with inverse material modeling using industrial process measurements.

(3) For other processes or other target values, i.e. in ring rolling, the closed loop process control may play an important role. In such cases it is necessary and sometimes possible to include the process control algorithms as well as virtual sensors in the simulation system.

7. Acknowledgment

The authors gratefully acknowledge the financial support of our industrial partners (Hilti, ThyssenKrupp, Hydro Aluminium, Dillinger Hütte) as well as the “Deutsche Forschungsgemeinschaft” (DFG) for several research topics.

References

[1] A. Hauger, „Flexibles Walzen als kontinuierlicher Fertigungsprozess für Tailor Rolled Blanks“, Ph.D.-Thesis RWTH Aachen (2000)

[2] R. Kopp, C. Wiedner and A. Meyer, „Flexible Rolled Sheet Metal and Its Use in Sheet Metal Forming“, Advanced Material Research, 6-8 (2005), pp. 81-92

[3] R. Kopp and P. Boehlke, A New Rolling Process for Strips with a Defined Cross Section, CIRP Annals – Manufacturing Technology, Vol. 52, 1 (2003), pp. 197-200

[4] H. Utsunomiya, Y. Saito, M. Matsueda, Proposal of a new method for the spread rolling of thin strips, Journal of Materials Processing Technology 87, (1999) pp. 207-212

[5] M. Abo-Elkhier, A modified method for lateral spread in thin strip rolling, Journal of Materials Processing Technology, Vol. 124, 1-2, (2002) pp. 77-82

[6] D. Dávalos Julca, T. Förster, B. Wietbrock and G. Hirt, Lightweight Design by Flexible Rolling and Strip Profile Rolling, Steel Research International (2011)

[7] P. Groche, M. Mirtsch, G. Hirt, D. Dávalos, Herstellung von Rohren mit flexiblem Wanddickenverlauf durch Walzprofilieren von bandgewalztem Vormaterial. FOSTA Abschlussbericht (2010)

[8] M. Ferry, Direct strip casting of metals and alloys, Woodhead Publishing (2006)

[9] M. Daamen, T. Förster and G. Hirt, Experimental and Numerical Investigation of Double Roller Casting of Strip with Profiled Cross Section, Steel Research International (2011)

[10] M. Carruth, J. Allwood, The forming of variable Cross-section I-Beams by Hot Rolling, ICTP (2011)

[11] Jenkouk, V.; Hirt, G.; Franzke, M.; Zhang, T. Finite element analysis of the ring rolling process with integrated closed-loop control, CIRP Annals - Manufacturing Technology, Volume 61, Issue 1, pp. 267–270 (2012)

[12] Jenkouk, V.; Hirt, G.; Seitz, J. Numerical simulations supporting the process design of ring rolling processes, The 11th International Conference on Numerical Methods in Industrial Forming Processes: NUMIFORM 2013. AIP Conference Proceedings, Volume 1532, pp. 695-700 (2013)

[13] A. Melzner, G. Hirt, "Roll bonding of two materials using temperature to compensate the material strength difference", ICTMP 2014

[14] M. Bambach, M. Pietryga, A. Mikloweit, G. Hirt, "A finite element framework for the evolution of bond strength in joining-by-forming process", Journal of Materials Processing Technology, vol. Special Issue "Joining by forming" (2014)

[15] W. Zhang and N. Bay, "A Numerical Model for Cold Welding of Metals," *Annals of the CIRP Vol. 45,* pp. 215-220, 1996.

[16] W. Zhang and N. Bay, "Cold Welding - Theoretical Modeling of the Weld Formation," Welding Research Supplement*,* pp. 417-420, 1997.

[17] A. Mikloweit, M. Bambach, M. Pietryga, G. Hirt, " Development of a testing procedure to determine the bond strength in joining-by-forming processes, International Conference on Tribology in Manufacturing Processes & Joining by plastic deformation" (2014)

[18] T. Romans and G. Hirt, Rolling of Drag Reducing Riblet Surfaces, AIAA (2010)

[19] G. Hirt and M. Thome, Large area rolling of functional metallic micro structures. Prod. Eng. Res. Devel. (2007) 1, pp. 351-356

[20] J. Pöplau, T. Romans, M. Bambach and G. Hirt, Riblet-rolling of clad AlCu4Mg1 sheets – passive drag reduction in aeronautics, Mailand: Associazione Italiana di Metallurgia – ISBN: 9788885298958 (2013)

[21] P. F. Bariani, T. Dal Negro, S. Bruschi. Testing and Modeling of Material Response to Deformation in Bulk Metal Forming, CIRP Annals - Manufacturing Technology 2004, Vol. 53, 573–595.

[22] T. Kárman, Zeitschrift für Angewandte Mathematik und Mechanik 5, 139-141 (1925).

[23] J. H. Beynon and C. M. Sellars, The Iron and Steel Institute of Japan 32, 359-367 (1992).

[24] K. Minami, F. Siciliano, T. M. Maccagno and J. J. Jonas, The Iron and Steel Instiutute of Japan 36*,* 1507-1515 (1996).

[25] P. Montmitonnet and P. Buessler, The Iron and Steel Instiutute of Japan 31*,* 525–538 (1991).

[26] F. Roters, P. Eisenlohr, L. Hantcherli, et al., Acta Materialia*,* 58 (4), pp. 1152-1211, (2010).

[27] D. Helm, A. Butz, D. Raabe and P. Gumbsch, Journal of the Minerals, Metals and Materials Society 64*,* 26-33 (2011).

[28] C. Brecher, M. Esser, S. Witt. Interaction of manufacturing process and machine tool, CIRP Annals – Manufacturing Technology 2009, Vol. 58, 588–607.

[29] Z. W. Wang, J. P. Fan, D. P. Hu, C. Y. Tang, C. P. Tsui. Complete modeling and parameter optimization for virtual ring rolling, International Journal of Mechanical Sciences 2010, Vol. 52.

[30] J. G. Lenard, M. Pietrzyk, L. Cser, Mathematical and Physical Simulation of the Properties of Hot Rolled Products, Elsevier, Kidlington, Oxford 1999.

[31] S. Seuren, J. Seitz, A. Krämer, M. Bambach, G. Hirt, „Accounting for shear deformation in fast models for plate rolling". Product Engineering (2013)

[32] C. M. Sellars, J. A. Whiteman. Recrystallization and Grain Growth in Hot Rolling, Metal Science Journal 1979, Vol. 13.

[33] C. M. Sellars. Modeling Microstructural Development during Hot Rolling, Mats. Sci. Tech 1990, Vol. 6, 1072–1081.

[34] J. J. Jonas. The Hot Strip Mill as an Experimental Tool, ISIJ 2000, Vol. 40, 731–738.

[35] J. Lohmar, M. Bambach, G. Hirt, T. Kiefer, D. Kotliba, M. Jochum, S.Seuren, „Fast and accurate force prediction for high quality heavy plates by a state of the arte rolling model calibrated from mill data via inverse techniques". ESTAD (2014)

[36] J. Lohmar, M. Bambach, G. Hirt, „The Precise Prediction of Rolling Forces in Heavy Plate Rolling Based on Inverse Modeling Techniques". Steel Research International (2014), accepted for publication