Digitizing Rollforming with Smart Sensors

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Abstract. Roll forming is a highly productive manufacturing process for complex profiles or precision tubes used in automotive, aerospace, building and many other industries. Shorter product life-cycles and increasing product customization require new manufacturing concepts. Digitalization enables companies to cope with these new challenges. Digitized machines and processes become one of the key factors in advanced roll forming. The application of smart sensors is a first step towards digitized roll forming. Edge devices enable the connection of different types of sensors in order to form smart objects which in turn can be assembled into smart factories. The better quality of collected smart data allows, for instance, the development of new roll forming applications and more detailed FE roll forming simulations. Higher flexibility in roll forming production and smaller lot sizes require new and fast methods for choosing the right roll forming line and setting it up. This paper presents a new model, based on FE-simulations without friction, for prediction of torques in roll forming lines, supporting the selection of roll forming lines or machine parameters. A semi analytic model is derived to predict the required driving torques of the rolls for different machine configurations without performing additional time consuming FE-simulations. The model is verified with data acquired by smart sensors installed in a 3D roll forming line. First results of this approach are presented and show the possibilities of the digital twin concept.

INTRODUCTION AND STATE OF THE ART

In roll forming a flat sheet metal strip is bent to a final profile by the application of rotating tools. Usually, numerous pairs of roll tools are in contact with the sheet, driving it through the roll forming line due to friction. As the rolls are contoured with cylindrical and conical elements one can observe different circumferential speeds in the contact zones between the sheet and the rolls. Thus, at the same time, positive, negative and zero sliding velocities can exist in a single roll. An important task of a roll tooling designer is the determination of a theoretical driving diameter for each roll, in order to design the appropriate gears in a roll forming line. No clear indication of how to calculate this driving diameter can be found in the literature, also Halmos [8] does not describe a calculation method.

Usually, finite element simulations are used for validating the forming strategy, and for selecting the appropriate roll forming lines. These simulations are time consuming due to the complex material behaviour, intense contact between rolls and sheet, a high number of forming steps and also due to friction. Moreover, to improve the prediction quality of the finite element simulation a fine mesh needs to be applied increasing the computational costs [9].

As manufacturing becomes more and more flexible, production lines are not always known at the start of the simulation process. In order to get the correct gear ratios and the required torques for the forming rolls, a new simulation must be set up before starting production. As a simulation can take several days, very often the engineers do not perform additional simulations and run into troubles later during the setup of the new line.

A new semi-analytical model tries to predict roll torque and sheet velocity as well as power consumption using results form already performed friction-less forming simulations. Using the configuration settings of the selected roll forming line, set up data can easily be obtained and sent to the machine setters.

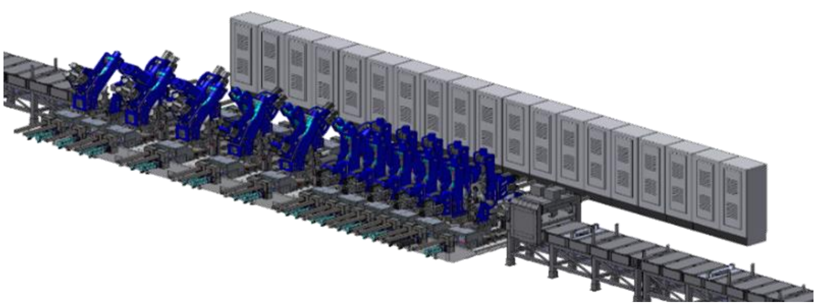
In a first step, experimental tests have been performed with a special 3D roll forming line for truck long members manufactured by data M Sheet Metal Solutions GmbH, Valley. In this line, all forming rolls are independently driven by servo drives, so velocity and torque of each roll can be individually set up. Smart sensors allow to read inputs from the machine's axes, using built-in computational resources to perform predefined functions, calculate drive parameters and pass on the data to databases. Next, a complex roll forming finite element simulation with COPRA® FEA RF has been set up to perform a simulation with driven rolls including friction effects, in order to compare both measurement and simulation results and to obtain a basis for validating the developed semi-analytical roll torque prediction model. Results obtained with the new model are compared to experimental and simulation results.

MATERIALS AND METHODS

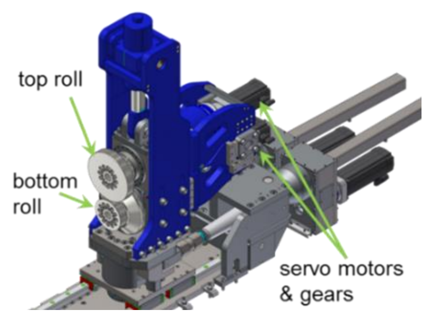
To determine the required torques, roll and sheet velocities in a roll forming line, an adequate testing method had to be found. Standard roll forming lines are usually equipped with only one central motor with fixed gear ratios between all top and bottom rolls. So far it has been difficult to perform the proposed tests in an industrial environment.

The approach applied in this paper makes use of a flexible 3D roll forming machine [2]. More than 50 different variations of U-channels, unsymmetrically variable on both sides, are manufactured on this line. Figure 1(a) shows the layout of the line. The high number of profile variations require special mechanical and control concepts [3], as the programming of a new profile is only done by software. The forming path is defined with the help of a simulation tool [1] and then the result of the forming path together with some technological parameters are transferred to the control system. All the machine settings are performed by electromechanical actuators. Each forming stand has individual servo driven top and bottom forming rolls (Figure 1(b)). They are equipped with smart sensors which acquire, besides other parameters, the rotational speed and the current of the servo motors and convert the latter value to the corresponding torque value. All measured data are stored via the OPC UA communication protocol in a centralized data base where they can be accessed later for the data analysis.

This industrial 3D roll forming line for truck long members has been used for the basic forming tests and measurements. For the test, a steel strip (thickness: 7mm, width: 272,5mm, length 9220mm) was used. The plastic material properties were: YS = 650 MPa, UTS = 700-880 MPa, A5 = 12%.



(a)



(b)

Figure 1. (a) Industrial 3D roll forming line, (b) singe servo controlled roll forming stand

Test method applied

A U-channel with a leg height of 65.2mm has been formed. During the test each station was acting independently, therefore, no interactions like pushing or pulling of the sheet has taken place. The top rolls' rotational speed has been kept constant, only the rotational speed of the bottom rolls was varied. Eight different gear ratios between top and bottom rolls were realized (see Table 1). The target velocity of the strip was 83.33mm/s (5.00 m/min). The velocity of the strip, the rotational speed and the torque of the rolls was measured.

Results of the forming tests

Figure 2(a) shows a typical result of the forming test in station 1 with 8 different gear ratios. The sheet velocity (in red) remains constant until the maximum circumferential velocity at the biggest diameter in contact of the bottom roll (in light blue) drops under the constant velocity of the top roll (in green) at sheet position 8700mm. The minimum circumferential velocity at the smallest diameter in contact of the bottom roll (in dark blue) does not influence the sheet velocity.

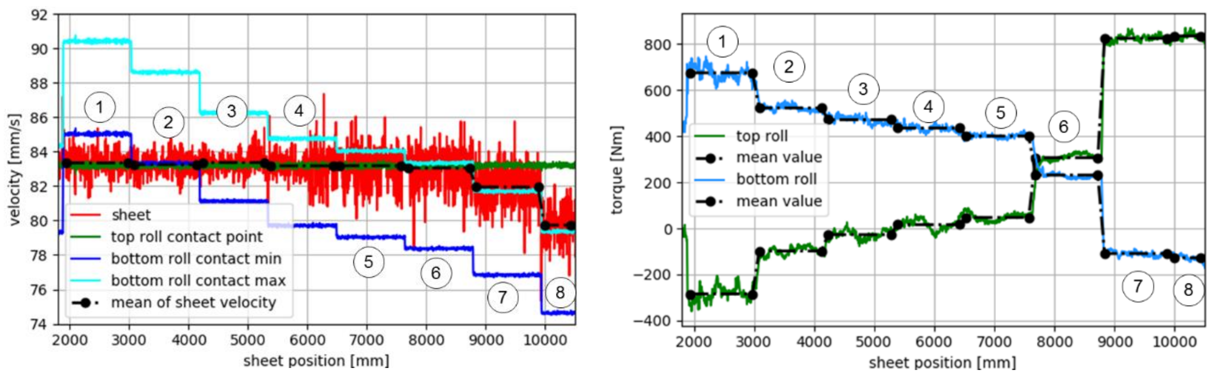
It can be concluded that in the case of station 1, the roll with the smallest maximum contact velocity determines the overall sheet velocity. Increasing the rotational speed of the bottom roll does not increase the overall velocity of the sheet as the top roll contact point is slower (stage 1-5).

Table 1. Levels of angular velocities $\boldsymbol{\omega}$ and gear ratios $\boldsymbol{i}$

$Stage$	ω_{top}	ω_{bot}	$i = \omega_{top}/\omega_{bot}$
1	0,5354	0,8695	0,6158
2	0,5354	0,8521	0,6284
3	0,5354	0,8295	0,6455
4	0,5354	0,8150	0,6570
5	0,5354	0,8081	0,6626
6	0,5354	0,8013	0,6682
7	0,5354	0,7856	0,6816
8	0,5354	0,7631	0,7016

Figure 2(b) shows the measured data of the torque per roll corresponding to Figure 2(a) where positive values indicate feeding of the sheet and negative values indicate breaking. It can be seen that the gear ratio has a big influence on the roll torque. In situations where the bottom roll (in blue) is rotating faster (stages 1-5), the bottom roll is driving the sheet while the top roll (in green) is breaking or idling. Also, an inverse behaviour can be observed for gear ratios where the bottom roll is rotating slowly (stages 7+8). For the gear ratio of stage 6, where the fast contact points of top and bottom roll have the same velocity, both rolls are clearly feeding the sheet.

These results clearly demonstrate the potential of the optimization of the gear ratios in roll forming lines with respect to energy or wear, as high rotational roll speeds increase relative sliding velocities.



(a) (b)

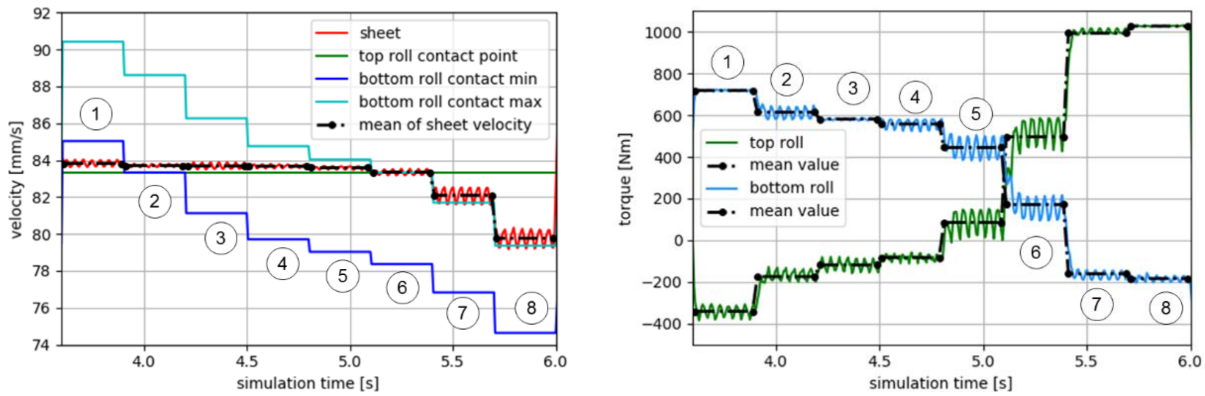
Figure 2. Results for station 1 maeasured and mean values (a) velocity and (b) torque

Simulation with friction

The above described test was also simulated with COPRA® FEA RF. A finite element model taking into account the friction between the sheet metal and forming rolls was used. The simulation model consists of one guiding station and one forming station. The rolls are independent rigid contact bodies with an analytical geometry description. The sheet is modelled by linear fully integrated hexahedral elements. Friction effects were modelled using the Coulomb model and a constant friction coefficient of 0.12. For the plastic material behaviour the isotropic *von Mises* law and a *Swift* hardening curve were used.

Simulation results

The presented simulation results are, like in the test, the velocity of the sheet and the roll torques. Figure 3(a) and Figure 3(b) show the raw simulation results for sheet velocity and roll torques. The noise in the graphs is a consequence of geometrical and time discretisation. The black curves represent the mean values for each gear ratio stage. Both diagrams show the same behaviour of sheet velocity and roll torques as measured during the experimental test. The simulation results show, that the model is able to represent the real test conditions and the investigated effects.

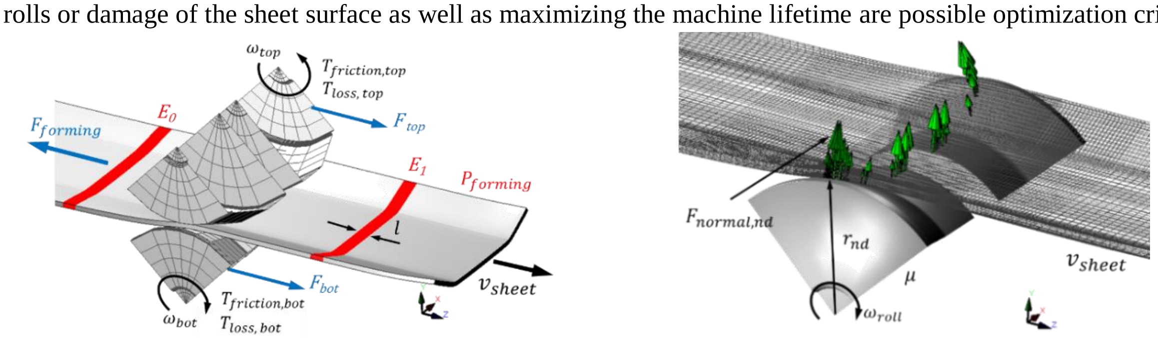


(a) (b)

Figure 3. Simulation results and mean values for station 1, (a) velocity and (b) torque

SEMI-ANALYTICAL TORQUE CALCULATION MODULE IN COPRA® FEA RF

The semi-analytical torque calculation module in COPRA® FEA RF, is based on a standard roll forming FE simulation without friction effects. After collecting the contact force and forming energy information from the simulation results, the module is able to calculate the sheet velocity and the roll torques in a time saving way. This enables the process designer to try out different gear ratios without running a time consuming FE Simulation and optimize the machine setup in regards of sheet velocity, roll torques and energy consumption. Also, minimizing wear of rolls or damage of the sheet surface as well as maximizing the machine lifetime are possible optimization criteria.



(a) (b)

Figure 4. Energy, forces and geometrical values in a basic finite element simulation model, (a) global values within one station, (b) contact normal forces of nodes in contact with the bottom rolls

Description of the module

In the following section the theoretical background of the semi-analytical model to calculate sheet velocity and roll torque is explained. Figure 4 (a) and (b) show the relevant parameters to set up the basic formulas of the semi-analytical model. As in the basic simulation, where friction is neglected, there is an equilibrium of forming force $F_{forming}$ and change in plastic energy per length, which is a constant for each individual station:

$$F_{forming} = \frac{E_1 - E_0}{l} = const \tag{1}$$

where: E_0 and E_1 is the plastic energy in a representative sheet portion of length l before and after leaving the station. Moreover, the forming power $P_{forming}$ of a station is dependent on the sheet velocity v_{sheet} and can be calculated by:

$$P_{forming}(v_{sheet}) = F_{forming}\, v_{sheet} \tag{2}$$

Furthermore, if friction is taken into account, there must be an equilibrium between forming force and the friction forces created by the rolls, which can be formulated like this:

$$F_{forming} = F_{bot} + F_{top} = \mu \sum_{i=0}^{n_{nodes}} \beta_i\, F_{normal,i} \tag{3}$$

where: F_{bot} and F_{top} are the total forces of the individual rolls, μ is the friction coefficient between sheet and rolls, n_{nodes} is the number of all nodes in contact, $F_{normal,i}$ is the contact normal force in one node and factor $\beta_i(v_{sheet})$ is used to distinguish between pure sliding and sticking situations in a contact point. Factor β_i is depend on the relative (sliding) velocity v_{rel} between the sheet and a contact point.

$$v_{rel}(v_{sheet}) = v_{sheet} - \omega_{roll}\, r_{nd} \tag{4}$$

where: ω_{roll} is the angular velocity of the roll and r_{nd} is the radius of the node in contact
Below a certain relative velocity $v_{rel,limit}$ it is assumed that: $F_{friction,nd} \leq \mu\, F_{normal,nd}$. For relative velocities greater than $v_{rel,limit}$, $F_{friction,nd} = \mu\, F_{normal,nd}$ applies. Therefore $\beta_i(v_{sheet})$ is:

$$\beta(v_{sheet}) = \begin{cases} 0.0 \ldots 1.0, & abs(v_{rel,nd}) \leq v_{rel,limit} \\ 1.0, & abs(v_{rel,nd}) > v_{rel,limit} \end{cases} \tag{5}$$

The implemented algorithm searches for β_i until the force equilibrium (3) is fulfilled. The known β_i allow the calculation of the friction torque per roll $T_{friction,\,roll}$ with:

$$T_{friction,\,roll} = \mu \sum_{i=0}^{n_{nodes}} \beta_i\, F_{normal,i}\, r_i \tag{6}$$

To find the sheet velocity for specific angular velocities of the rolls, the assumption of minimal power within the system of rolls and formed sheet is applied.

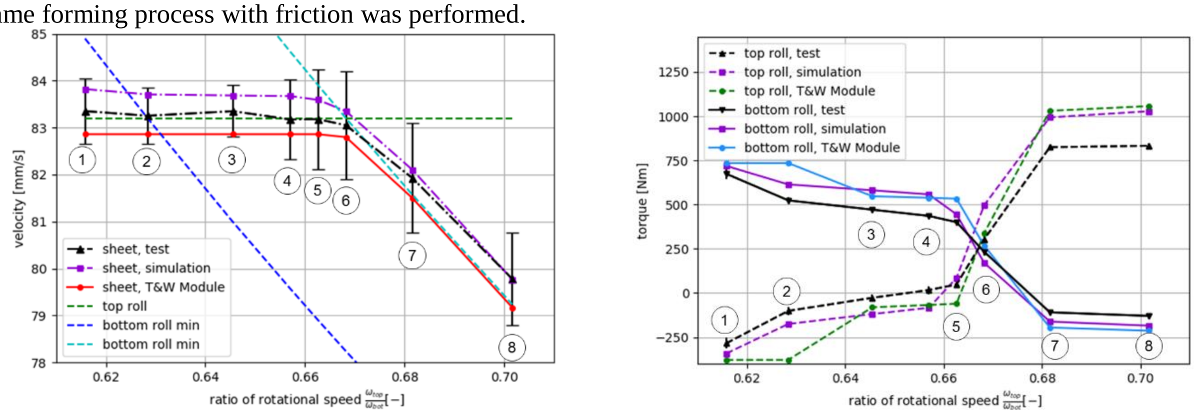
As the friction torque of the rolls and the forming power are dependent on the assumed sheet velocity, the algorithm tries to determine v_{sheet} by finding the minimum of the total power in the system:

$$\underset{v_{sheet} \geq 0}{\arg\min}\left(P_{forming}(v_{sheet}) + \sum_{i=0}^{n_{rolls}}\left(T_{friction,\,i}(v_{sheet}) + T_{loss,\,i}\right)\omega_i\right) \tag{7}$$

where $T_{loss,\,i}$ is the torque due to the gear loss per roll and n_{rolls} is the number of acting rolls.

Validation of the module

The proposed model was validated by comparing both experimental and complex simulation results to the data calculated with the help of the new semi-analytical module. A standard finite element model without friction was set-up to simulate the first station of the U-channel forming process. Also, a complex finite element simulation of the same forming process with friction was performed.



(a) (b)

Figure 5. Comparison of measured, simulated and calculated (module) values, (a) velocity and (b) torque

In Figure 5(a) the rotational speeds of the top and bottom rolls, together with the resulting sheet velocities of the three methods are presented. The comparison of the data calculated by the semi-analytical model with the data obtained from a simulation with friction and the measured experimental data show an overall good accordance. The maximum difference in all three cases lies within a range of 1.1%. Until stage 6 the sheet velocities for all three cases remain constant. Once the maximum bottom roll speed drops below the speed of the top roll, the resulting sheet velocity also drops. In all three cases this behaviour is well represented. The lower the resulting sheet velocity, the better the experiment and the complex simulation model with friction are corresponding. The simulation results as well as the calculated values are within the standard deviation of the measured data for all investigated gear ratios.

The roll torques presented in Figure 5(b) show that the simulation and the semi-analytical model are able to describe the experimentally observed effects of feeding and breaking for all investigated gear ratios. However, both numerical models seem to overestimate the torques for the top and for the bottom roll. In stage 2 the semi-analytical model differs from the experimental data drastically whereas the advanced simulation model with friction has a better fitting. In stages 7 and 8 the numerical models predict a higher torque for the top roll as measured in the experiments. Nevertheless, the proposed model is able to describe well the qualitative behaviour in one forming stand.

Possible reasons for the differences of the roll torque values are deviations from the perfect setup parameters in the roll forming line due to elastic deformation. Also the type of friction model applied in the simulations can cause some differences as it e.g. does not differentiate between sliding and static friction.

DISCUSSION AND CONCLUSION

In this paper we have presented a novel semi-analytical model allowing to calculate the sheet velocity and the torques and total power for given angular roll velocities in roll forming lines. It combines information from a basic roll forming simulation as well as machine parameters and acts as a digital twin of the forming process in terms of velocities, power and roll torques. This method allows the tool designer to determine fast and efficiently necessary machine setup data without setting up new and costly finite element simulations. Due to the development of smart sensors and an appropriate machine design, a new type of roll forming experiments have become possible.

The experimental results are in good agreement with the results obtained from the finite element simulations and from the new semi-analytical model. This shows the capabilities of the new model to predict the sheet velocity, the roll torques, the power consumption and wear on the sheet material in a roll forming line. In order to improve the overall quality of the model, in a future work we will integrate the interaction between multiple forming stations in the semi-analytical model.

Another promising aspect of the new semi-analytical model is the fact that it can be implemented in a machine control software like COPRA® Adaptive Motion Control as it supports machine learning and self-optimizing methods for the roll forming lines in terms of power consumption, sheet velocity, roll torques or wear. An in-process real time optimization of the roll forming process becomes possible as the time consuming bottleneck of additional advanced finite element simulations for each new machine configuration is eliminated.

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