Energy efficient roll forming processes through numerical simulations

To cite this article: T Traub and P Groche 2018 J. Phys.: Conf. Ser. 1063 012182

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Energy efficient roll forming processes through numerical simulations

T Traub and P Groche
Technische Universität Darmstadt, Institute for Production Engineering and Forming Machines, Otto-Berndt-Straße 2, 64287 Darmstadt, Germany
traub@ptu.tu-darmstadt.de

Abstract. Due to ongoing efforts to mitigate climate change especially large scale manufacturing methods such as roll forming have to be optimized with respect to energy consumption. The required amount of drive power in roll forming is strongly affected by the rotational velocity of the tools. Due to the contoured shape of the rolls resulting in varying circumferential speed, the relative speed between tool and blank sheet can be positive, negative or zero. In consequence, neighboring sections of the same forming roll can accelerate or decelerate the blank sheet. Inappropriate speed ratios between different shafts cause some shafts to decelerate the blank sheet while other shafts have to compensate this deceleration and waste energy. Presently, the rotational speed of the shafts is mainly chosen based on the operator’s experience leading to a high risk of an energy inefficient process setup. This paper demonstrates how numerical simulations can optimize the energy demand in roll forming and validates the results experimentally. The drive power for each individual shaft is minimized by balancing accelerating and decelerating tool sections. Thus, the optimal rotational velocity for each shaft is derived. The numerical simulation predicts an energy saving potential of 50 %. However, due to limited control accuracy only 14 % could be realized in experiments to date.

1. Introduction
The efficient use of energy is an essential objective of current political projects. About 200 nations agreed to make joint efforts to limit the rise in temperature due to man-made climate change at the climate summit in Paris in 2015 [1]. The industrial sector is responsible for about 55 % of global energy consumption [2] and 35 % of global CO$_2$ emissions [3]. Therefore, great efforts are required to increase energy efficiency in this area in order to reach the intended climate targets. The production and processing of steel accounts for about 25 % of industrially induced CO$_2$ emissions [3]. Furthermore, 35 % to 45 % of flat steel products produced in North America are processed by roll forming [4]. In addition to increasing energy efficiency in primary steel production, the energetic optimization of the roll forming process thus promises to make a significant contribution to reducing the energy demand of industry.

2. State of the art
Roll forming is a continuous sheet metal bending process employing rotating tool movements [4]. Multiple pairs of contoured rolls pull the sheet through the roll forming machine due to friction forces and form it at the same time without intentionally changing the sheet thickness [4]. Figure 1 (a) illustrates schematically a roll forming process forming an initially flat metal strip into a U-channel.
The circumferential speed of the tools varies, due to the changing tool diameter of the forming rolls. Hence, the slip \( \Delta v \) (equation 1) describing the relative speed between the (local) circumferential tool velocity \( v_c \) and the constant feed speed of the blank sheet \( v_0 \). \( v_c \) is represented by the product of local tool radius \( r \) and rotational velocity \( \omega \). The slip \( \Delta v \) can be positive, negative or zero. Sections subjected to a positive slip accelerate the blank sheet while sections with a negative slip decelerate it. If sections with negative relative speed outweigh the sections with a positive one, a whole shaft might decelerate the blank sheet and thus waste energy.

\[
\Delta v = v_c - v_0 = r \cdot \omega - v_0
\]  

(1)

The distribution of the slip is affected by the choice of the driving shaft diameter describing that section of the cross section where the slip is considered to be zero. Figure 1 (b) illustrates the effect of a modified driving shaft diameter marked by \( r_0 \) on the distribution of \( \Delta v \). However, to date only limited support for the designer regarding the choice of \( r_0 \) is available. Even Halmos’ roll forming handbook summarizing the comprehensive knowledge on roll forming technology and tool design only provides qualitative suggestions regarding the choice of \( r_0 \) [4].

![Figure 1](image-url)

**Figure 1.** Schematic illustration of a roll forming process (a) and slip conditions (b).

In general, there are three possibilities to influence the slip between forming rolls driven by one shaft and the blank sheet. Firstly, the feed speed of the blank sheet can be modified. However, a change of the feed speed affects the slip at all shafts simultaneously and is, therefore, not applicable to optimize the slip at one particular shaft only. Secondly, the rotational velocity of the shaft can be adjusted. The prerequisite for this strategy is that each shaft is powered by an individual motor so that the rotational velocity of different shafts is independently adjustable. Last but not least, the diameter of the rolls can be changed slightly resulting in an altered circumferential speed, too. This strategy requires, however, a reliable prediction of slip during the design of the tooling.

A study by Paraklias analyses the potential to save energy in a roll forming process by means of optimizing the bending angle sequence, the tool gap between top and bottom roll, the distance between forming passes, the feed speed of the blank sheet and the simultaneous change of all tool diameters [5]. However, the adjustment of the rotational velocity or diameter of individual rolls affecting the slip conditions has not been considered here.

Aiming at the energetic optimization of a roll forming process, Eichler calculates analytically the most appropriate \( r_0 \) balancing accelerating and decelerating tool sections [6]. For his calculation, however, he assumed a homogenous distribution of the contact pressure between forming rolls and blank sheet across the profile’s cross section. Recent research suggests that this assumption is not applicable and the contact pressure distribution is inhomogeneous [7].

Numerical simulation models developed during the last years provide the opportunity to consider the inhomogeneous distribution of the contact pressure for the optimization of the slip distribution. An overview over different studies is given in [8]. For the understanding of this paper, especially simulation models analyzing the drive torques in roll forming are relevant.

Larrañaga [9] analyzes the drive torques occurring in roll forming a U-channel. In order to accelerate the simulation, he combines sections of coarser and finer meshes. He finds deviations between experimental and numerical results of up to 300 %. Lindgren [10] analyzes the production of a U-channel as well. The differences between experimental and numerical results decrease to less than
40\% due to a reduced coefficient of friction. Müller et al. consider the compliance of the roll forming mill and reach a virtual match of torques determined in experiments and simulations [11]. These studies demonstrate that the realistic modelling of the torques in numerical simulations of roll forming is possible.

3. Objective and approach
This study aims at reducing the energy demand of a roll forming process by balancing accelerating and decelerating tool sections by means of numerical simulations. The drive torques at each shaft are closely related to the total power demand. Therefore, the results of the simulations are used to predict the drive torques under consideration of the inhomogeneous distribution of the contact normal pressure. Aiming at drive torques close to zero, the circumferential speed at each roll and thus the energy demand of the whole process is optimized by adapting either the tool radii or rotational velocities, respectively.

The drive torque $T$ applied by a shaft can be estimated by integrating the product of shear stress $\tau$ and local radius of the forming roll $r$ across the contact area $A$ between blank and forming rolls driven by that shaft (equation 2).

$$T = \iint \tau \cdot r \, dA$$  \hspace{1cm} (2)

The absolute value of $\tau$ is determined by multiplying the local contact normal stress $\sigma_N$ by the coefficient of friction $\mu$. The direction of $\tau$ is crucial for the distinction of accelerating and decelerating tool sections. The slip $\Delta v$ is used to determine the direction of $\tau$. Defining $T$ positive (negative) if the blank sheet is accelerated (decelerated) by the shaft, a positive (negative) $\Delta v$ corresponds with an accelerating (decelerating) $\tau$. Therefore, using the signum function of $\Delta v$ equation 2 is converted into equation 3.

$$T = \iint \mu \cdot |\sigma_N| \cdot r \cdot sgn(\Delta v) \, dA$$  \hspace{1cm} (3)

Equation 3 considers the shear stress across the whole contact area unless $\Delta v$ equals zero. However, this condition applies only to one line across the contact area and is, therefore, considered to be negligible in comparison to the whole contact area.

The chosen approach derives $\sigma_N$ from a numerical simulation. Furthermore, knowing the intended feed speed of the blank sheet $v_0$, $sgn(\Delta v)$ only depends on $v_c$ (equation 1) which is individually adjusted at each shaft by modifying either $\omega$ or $r$, respectively, so that $T$ calculated by equation 3 equals zero. The optimized process parameters are implemented to the numerical simulation and the resulting torques are evaluated and compared to the initial ones.

3.1. Sample process
The approach is demonstrated at a process forming a blank sheet (length 1.5 m, thickness 2.0 mm, width 175 mm, grade S235JR) into a U-channel with inner bending radii of 3 mm. The profile, sequence of bending angles $\alpha$ and the roll forming machine are depicted in figure 2. The distance between the passes is 525 mm. Passes one to three employ top and bottom rolls only (diameters in the web section: 250 mm) while passes four to six use side rolls as well (diameters of bottom / top rolls in the web section: 250 mm / 300 mm; diameter of side rolls: 150 mm). Each top and bottom shaft is powered by a DC shunt motor, the side rolls are not driven. The initial $\omega$ is calculated using the intended blank sheet velocity of 6 m/min and the respective tool diameter in the web section. For the test of the optimized rotational velocities the calculated $\omega$ are set. The drive torque of each motor is observed using a load cell type U2AD1-1 t built by HBM fixing the rotatable supported motor housing with a lever of 0.216 m (figure 2 (c)). The reaction moment of the housing and thus the drive torque is calculated multiplying the sensor signal by the lever of the fixation and the gravitational constant. In order to respect the interaction of different forming passes, in each pass only that section of the measurement data is considered for the torque evaluation while the blank sheet is formed at least by the previous and consecutive forming stand, too. All measurements are repeated three times.
3.2. Modelling strategy in the numerical simulation

The numerical model has to find a trade-off between efficient calculation implicating a coarse mesh and a high resolution of the distribution of $\sigma_N$ requiring a fine mesh. Thus, a submodel [8] is employed to provide the high resolution of $\sigma_N$. In the global model a blank sheet of 1.5 m length is roll formed into a U-channel. Furthermore, the blank sheet has an inlet zone guaranteeing a smooth inlet into the forming stands. Symmetry along the x-z-plane is considered. The blank sheet is driven by rotating forming rolls due to friction. The coefficient of friction ($\mu = 0.1$) has been determined in strip drawing tests. Drive rolls ensure that the blank sheet is inserted into the first pass. The top and side rolls are supported by springs (figure 3 (a)). While the tools are rigid the blank sheet is described by elastic ($E = 210,000$ MPa, $\nu = 0.3$) and plastic (flow curve determined from tensile tests) properties. The global model employs a structured mesh. The submodel is located at the centre of the global blank sheet in x direction in a fine meshed strip [8]. The mesh structure is depicted in figure 3 (b). $\sigma_N$ is evaluated across the top and bottom surface of the submodel. For the adjustment of the rotational velocities two strategies are considered. On the one hand, the calculated, optimized $\omega$ are implemented. On the other hand, in order to account for the fact that many industrial roll forming lines do not provide the option to change $\omega$ of single shafts, the intended circumferential speed is adjusted by modifying the tool radii while the initial rotational velocity is kept constant. Figure 4 (c) provides the equation to adapt the roll radii in the web section to these new conditions while $\omega$ is kept constant.

4. Results

4.1. Optimization predicted by the numerical simulation

Figure 4 (c) gives an overview over the initial and optimized $\omega$ and the calculation of the optimized roll radii. Figure 4 (a) compares the torques predicted in a numerical simulation for the initial $\omega$ and optimized $\omega$ (figure 4 (b)). The results show that negative torques no longer apply after the optimization. Furthermore, the absolute values of the positive torques at the bottom shafts decline. In total, a reduction of energy demand by 51 \% is predicted if the optimization strategy is employed.
4.2. Experimental validation

For the validation of the numerical model, $\sigma_N$ predicted in simulations is compared to measurements of $\sigma_N$ using Fujifilm’s prescale pressure measurement film [12]. In order to ensure that the location of the evaluation in simulation and experiment is identical, the maximum $\sigma_N$ between top roll and blank sheet is considered for this comparison. The results show that the maximum difference between simulation and measurement is 15% (figure 5 (b)). Although the process setup has been double checked, small inaccuracies in the setup of the real process that are hardly detectable might cause some deviations. The measurement uncertainty of the pressure measurement film is 10%, if perfect measurement conditions with respect to humidity, temperature and load time are applied [12]. These perfect conditions are hardly achieved in roll forming. Furthermore, the simulation underestimates and overestimates $\sigma_N$ in different passes. Thus, the prediction of $\sigma_N$ seems realistic.

In addition, experimental and numerical results of $T$ are compared. In general, the results show a good accordance between experimental and numerical measurements (figure 5 (a)). In some cases (e.g. pass 1), however, the torque distribution between top and bottom shaft predicted by the simulation after the optimization does not match the experimental values. The reason for these small deviations is proposed to be the lower control accuracy of the real process in comparison to the simulation. The reduction of the torques in pass 6 top is clearly overestimated by the simulation. This finding occurs due to the high sensitivity of the real roll forming process with respect to the position of the side rolls in pass 6. Small deviations from the perfect set up that cannot be gauged with ordinary measurement devices are the cause of this mismatch. The general trend of decreasing torques, however, is evident in both simulation and experiment.

Comparing the results derived from simulations optimizing either $\omega$ or the roll radii suggests that both methods are equivalent. This is true at least as long as the changes of the roll radii are small compared to the initial radii.

Finally, the reduction of energy demand predicted in the numerical simulation (51%) and experiment (14%) is compared. Although the proposed optimization strategy reduces the energy demand in simulations as well as in experiments, the numerical simulation to date overestimates the energy saving potential. The qualitative behavior is, however, identical. There are three reasons that contribute to this overestimation. Firstly, the high sensitivity of the real forming process to the tool position of the side rolls in pass 6 contributes to this mismatch as explained previously. Secondly, due to the lower control accuracy of the real roll forming process, small deviations from the ideal velocity applied in the simulation occur that might cause additional, small deviations of the torques. Finally, the simple friction model which does not yet distinguish sliding and static friction might be another cause for deviations. A future distinction between sliding and static friction could solve this issue.
5. Discussion and conclusion

This paper presents a method for the optimization of the energy demand in roll forming processes. Numerical simulations predict an energy saving potential of up to 51%. An experimental validation of the approach indicates that the saving potential is overestimated by the numerical simulation. However, a positive impact on the energy demand is found in experiments as well. For this reason, the approach presented here can make a contribution to increase the energy efficiency of the mass production process of roll forming without large investments by optimizing the tool radii of new sets of rolls.

In order to enhance the quantitative accuracy of the numerical model, future work will implement more detailed friction models. An improvement of the control accuracy of the real forming process might enhance the energy saving, too. Last but not least, the demonstrated approach will serve as basis for an automatic mathematical optimization and thus be applied to other roll forming processes.

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