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ELASTIC TOOL BEHAVIOUR IN COLD ROLLING

REINER KOPP, MARTIN FRANZKE

Institute of Metal Forming, RWTH Aachen University, Germany
Corresponding Author: franzke@ibf.rwth-aachen.de (M. Frantzke)

Abstract

An important issue for realistic simulation of the cold rolling process is the consideration of the tools as elastic structures. The material flow is strongly influenced by the elastic deformation of the tools. Due to the enormous increase of the computer performance, this influence can be considered more and more realistically. This paper shows mainly the elastic behaviour of the working roll and discusses the influence on the geometry of the rolled strip.

Key words: modeling elastic effects in forming processes

1. INTRODUCTION

Beside reaching predefined mechanical properties, a major quality criterion especially in cold strip rolling is to meet very close geometric tolerances. Normally, after rolling no other process step can correct the thickness profile of the semi-finished product. The thickness profile has substantial influence on following forming processes, e.g. deep-drawing. The automotive industry applies metal sheets with a thickness profile that does not exceed a two-digit micrometer range.

The elastic deformation of the roll gap is caused by three different phenomena, which are superimposed in practice (Fig. 1). Due to the forming forces, the working roll will bend over its length, while in the area of contact to the strip it will flatten. In rolling mills with back up rolls, the working roll will also be compressed. Formerly circular cross sections thus differ from the original shape. All of these effects interact with the strip and have an impact on the thickness profile and flatness of the strip. The reason for roll deformation is the pressure distribution in the roll gap, which in sum equals the rolling force.

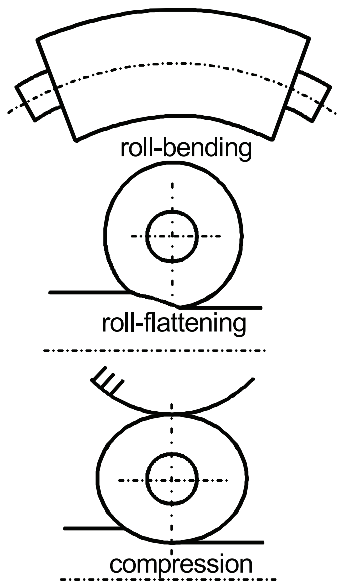

Fig. 1. Three elastic effects of the working roll

In cold rolling, strip tension in the rolling direction reduces the required rolling force. The strip tension applied is in a range of 0.2 – 0.6 times the yield stress. The elastic strain in the strip between the rolling stands resulting from this has considerable influence on the pressure distribution in the roll gap. Assuming incoming strip with a rectangular cross sec-

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tion and parallel working roll surfaces in a load free status, the pressure distribution in the roll gap generates a convex roll gap which is especially due to roll bending. These conditions cause an approximately parabolic thickness profile. Near the strip edge, the roll gap becomes narrow and causes more stretching than in the centre of the strip. One possible consequence is that the strip tension is transferred only through a small fraction of the cross section.

2. MATHEMATICAL MODELS

The necessity of considering at least the elastic deformation of the working roll has been known for more than 70 years (Prescott, 1924). In the beginning, the aim was the precise determination of the rolling force, torque and energy requirements (Jortner et al., 1960). But at least with the works of Bentall & Johnson (1969) it became clear that consideration of elastic roll deformation is necessary for a more general rolling theory, especially in the rolling of thin strip or foil.

Since the mid-1970's, the calculation of roll deformation is used to predict the strip's thickness profile and flatness. Above all, it was necessary to overcome the plane approach and advance towards a more general spatial treatment of the problem. To reduce the calculation effort, the development of the model was limited to major elastic parts of the rolling mill such as roll sets. The pressure distribution was provided as a known value. The elastic reaction of the roll set was calculated using approaches from advanced elasticity theory. The contour of the deformed roll gap can be understood as a thickness profile of the untreated strip. These approaches are used in industrial research until today. It is the low computation time and the achieved results that still make it attractive in comparison to more precise methods like Finite Element Analysis (FEA). Depending on the used model it can even be applicable for online models.

Usually in simulation of the rolling process with the FEA, the roll is assumed to be rigid, and there is no deformation. But with the beginning of the 1990's one can also find finite element approaches that take the elastic deformation of working roll or even roll sets into account. The method proposed in this paper works with an implicit Lagrangian finite element approach coupled with an elastic-plastic material law for the strip. The applicability of different finite element approaches has previously been discussed in (Kopp & Horst, 2000; Shangwu et al., 1999; Mackel, 1996; Sutcliffe, 2001; Hacquin, 1998).

3. CONCEPT OF MODELLING THE ROLLING PROCESS CONSIDERING ELASTIC EFFECTS

The simulation is divided into two paths. The right path in Fig. 2 contains the process simulation, and the left path the deformation analysis.

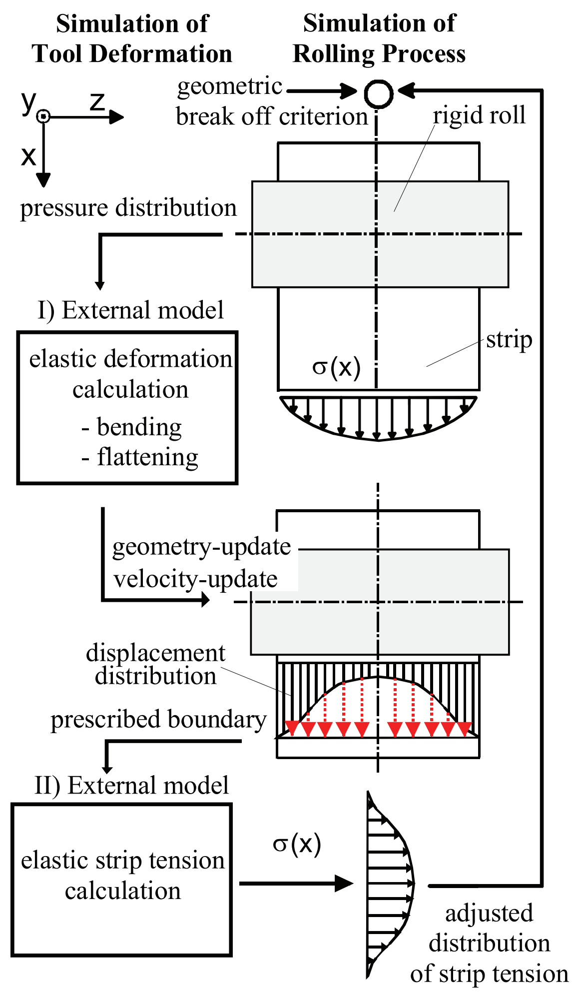

Fig. 2: Flow chart of presented concept for simulation rolling process considering elastic effects

The finite element analysis starts with a conventional simulation of the rolling process, with a rigid roll of ideal geometry (right side of Fig. 2). Strip tension is introduced to the model by giving the total force via an input file through the simulation. In the case of a rectangular profile over the width of the strip, the strip tension distribution is constant in the beginning. When the rolling force is constant, the rolling simulation becomes stationary. Normally, at this time – but any other time is technically possible as well– the contact forces between the boundary of the rigid tool and the strip are transferred to an external finite element model and used in a separate three dimensional finite element analysis as an external load distribution. Fig. 3 shows the functionality of the box called "external model I", in more detail. The roll deformation problem is handled as a static, linear elastic problem. Depending on the given boundaries, bending and flattening of the work roll are considered. The working roll model includes the bulk data due to the discretisation of the work roll. But due to its linear elasticity this problem can be solved directly. As a result of this simulation, a surface mesh is extracted from the deformed structure and transferred to the rolling simulation as an update of the geometry of the rigid roll. Because of the working roll deformation, the velocity field must also be adjusted.

At this point, the simulation is automatically restarted without strip tension. The aim is to impose a displacement characteristic to the strip that corresponds to the updated contour of the working roll, neglecting the influence of strip tension. Reaching steady state again, displacement values of a node row across the width that already passed the roll gap are read out. In Fig. 2, elements close to the edge are subject to larger strain than elements near the centre of the strip. The deformation distribution is similar to a parabola with negative characteristic. Without strip tension in the real process such deformation distribution would lead to waves along the strip edges. In the simulated process, this behaviour is inhibited by symmetry conditions in the x-z plane.

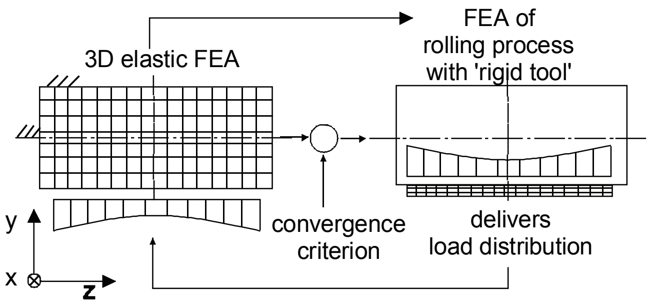

Fig. 3. External model I

The strip tension between the roll stands prevents the strip from these waves as long as the process continues. Due to the deformation distribution, the strip tension changes from a constant value over the width to a tension distribution, which is inversely proportional to the deformation condition. Originating from the displacement distribution, the complementary distribution is determined and marked with dashed arrows in Fig. 2.

$$d_i^{complementary} = (d_{\max} - d_i)$$

This distribution $d^{complentary}$ is inverted in its algebraic sign and transferred to a second external model. d_{max} means the maximum displacement achieved, and d_i is the displacement of node i. This static and elastic finite element model of the strip is fixed at one end. At the other end, the inverted displacement distribution becomes a prescribed boundary condition to the elastic strip model. The functionality of the second black box labelled "external model II" is explained in Fig. 4.

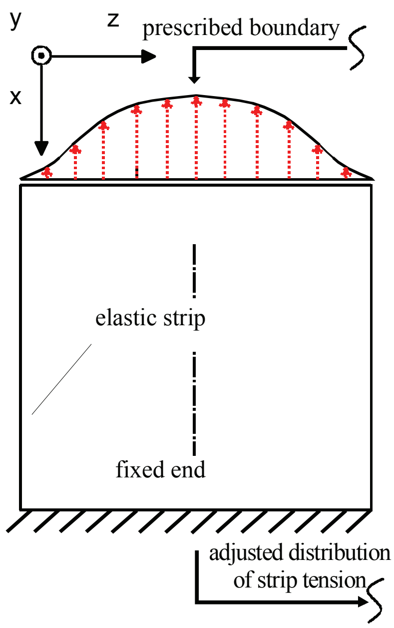

Fig. 4. External model II

With the data from the rolling process, an elastic strip tension simulation is carried out, delivering the qualitative characteristics of strip tension via the reaction forces at the fixed nodes. These characteristics correspond to the displacement distribution of the rolling model.

The total force between two rolling stands is constant, not influenced by the roll gap deformation. However, the strip tension distribution, changes. To ensure that the qualitative strip characteristics also fit quantitative requirements (total force), a correction factor is introduced, which is calculated from the ratio of the total strip force from the very beginning and the summarized nodal force from the elastic strip tension FEA. The qualitative strip tension distribution is scaled with this factor and the adjusted strip tension profile is transferred to the rolling simulation. To complete the run, a new data input is generated with updated values of the roll geometry, the rolling velocity, and the strip tension.

4. SOME RESULTS OF THE ROLLING SIMULATION

The usefulness of the above mentioned concept is validated with experimental data found in an investigation of a single-pass cold rolling process in a four-high mill. Table 1 shows the parameters of the rolling pass (Schroeder, 1967).

Table 1. Single pass cold rolling in a 4 high mill

Material: 85Cr7, flow curve from literature (Schroeder, 1967)	
Strip width	50 mm
Strip height	0.6 mm
Height reduction	33%
Velocity of the working roll	11 m/min
Friction coefficient	0.1
Strip force	750N

Fig. 5 shows the finite element model used for the analysis of the rolling process. Some essential data of this model and the two external models for the elastic analysis are summarized in Table 2.

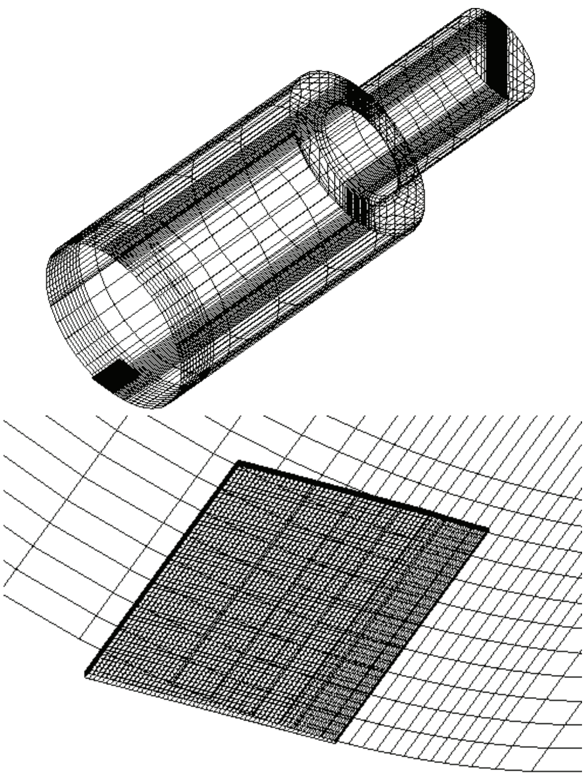

Fig. 5. Finite element model considering symmetry properties with a close up of the contact area

Fig. 6 shows the development of the deformation of the working roll contour. It shows the displacement of a row of nodes, located on the lower roll surface close to the outlet of the strip. The row is marked as the bold line in the sketch of the working roll in this chart. One can see how the roll as a whole bends and how the narrow strip is embedded into the roll. The characteristics of the deformed structure after the first and last pass through the entire simulation are plotted.

Table 2. Some Data of the Finite Element Model

Model of Rolling process	
Number of elastic-plastic elements	7830
Number of nodes	9912
Deformation model of the roll	
Number of elastic elements	10656
Number of nodes	12459
Strip tension model	
Number of elastic elements	7830
Number of nodes	9912

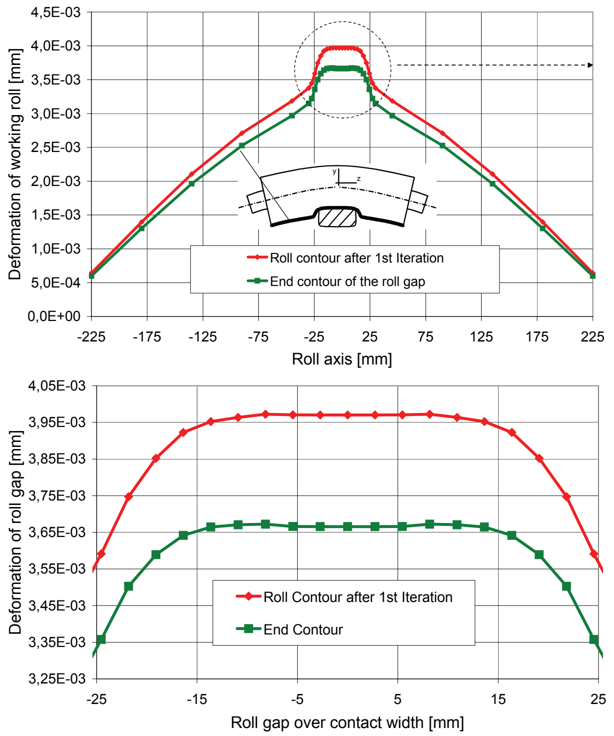

Fig. 6. Contour of the working roll along a nodal row close to exit of the strip (left), close up of the roll gap (right)

Fig. 7 shows the pressure distribution in the roll gap. The pressure distribution was computed after the last pass through the loop sketched in Fig. 7, is in line with experimental investigations. A characteristic is the forming of two vertices close to the edge of the strip.

The left plot in Fig. 8 shows the characteristic of the displacements of the above-mentioned nodal row that passes through the roll gap. It is significant for a convex roll gap, that the strip gets more strain from the midway through the edge. Corresponding to this, the right chart in Fig. 8 shows the achieved strip tension distribution. This graph corresponds to the constant start value of the strip tension. It can be realised that the strip tension decreases, coming closer to strip borders. With such a computation the simulation stability can be assured “a priori”. But in the present case there is no reason for concern, due to the small amount of strip tension.

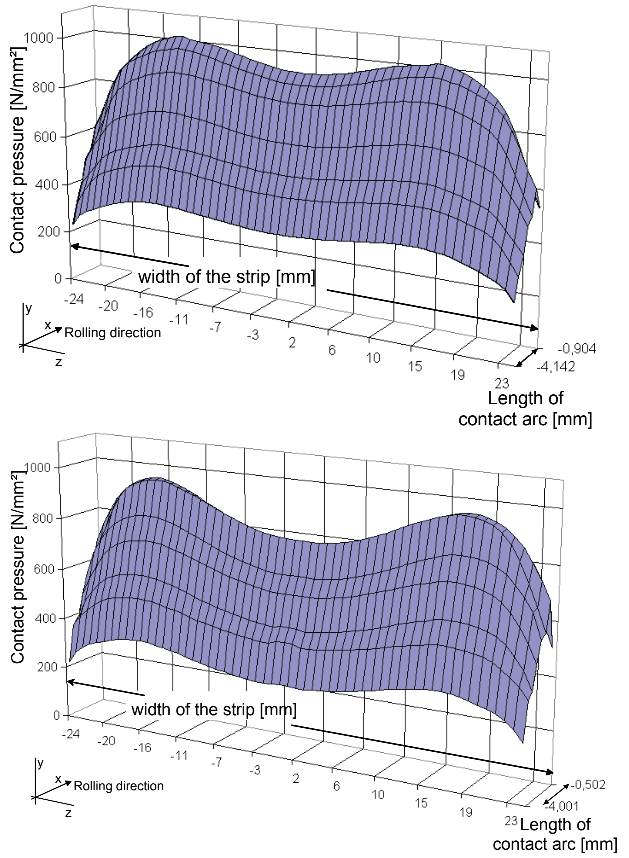

Fig. 7. Pressure distribution after the first (left) and the last iteration (right)

Simulation of forming processes with an implicit finite element method using a Lagrangian description can be accompanied with poor convergence. This can be avoided by supplying a finite element structure with sufficient number of constraints. In the present case, the finite element structure was already within the roll gap, before the rolling simulation started. This "drawn in" condition is a functionality of the pre-processor used which is part of LARSTRAN/SHAPE. Due to this geometric constraint at the very beginning of every rolling simulation the start up is without problems. The pass through the whole loop – with the two elastic analyses – is fully automated including the necessary data-transfer. In the present state, the program only stops after the deformation analysis of the working roll, to give the user the opportunity to fix the contact situation that slightly changes when embedding the geometry of the working roll to data input. In the future, this step also will run automatically without requiring user interactions. All simulations are carried out with the program LARSTRAN/SHAPE. LARSTRAN is embedded in the Pre- Post and Developing environment program PEP, under continuing development since 1992.

At present, the simulation time for 3 iterations, that means three passes through the whole loop, is about 72 hours. This time seems quite high, but there is some potential to accelerate the simulation. Firstly, the time or distance when the process is stationary, is defined in a conservative manner. Criterion of steady state is the rolling force which is defined as static, when the force is roughly constant for a sufficient amount of time. Secondly, the geometric convergence criteria have a quite severe lay out.

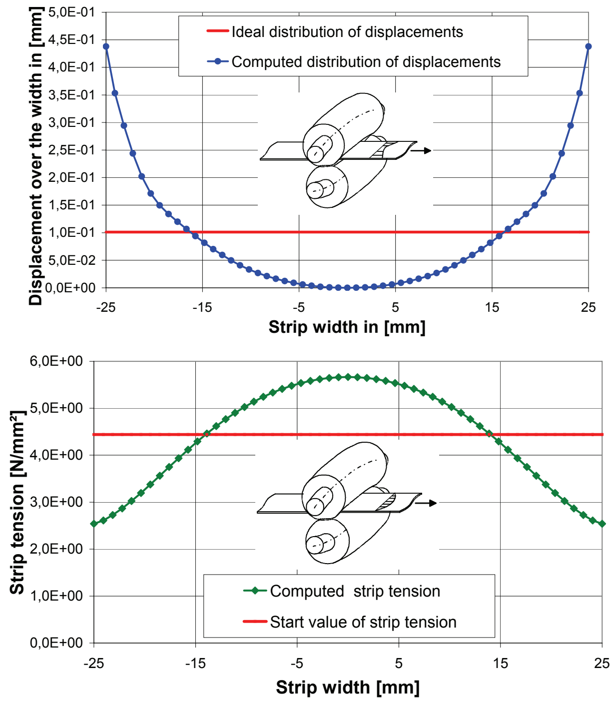

Fig. 8. Displacement distribution at the beginning of the Iterations (left) and therefore resulting strip tension (right)

Basically it becomes clear that, the most effective step is the first run through the loop. Every further run only leads to a very small improvement of the results. With that in mind, the simulation time can be cut down to 24 hour.

5. CONCLUSION

At present, only the elastic deformation of the working roll is simulated. Effects resulting from a back up roll were considered via restrained nodes of the upper side of the elastic working roll model. This status is unsatisfactory.

The simulation curve (Fig. 9) models the experiment data (Schroeder, 1967) very well. The comparison of the quantity shows that the numerical results are in average 5 micrometer higher in calculation than in experiment for this example. The reason for that is caused by the assumptions are made:

a) The roll flattening between working roll and back-up roll has been neglected. In the real rolling process the working roll shifts with the level of the mutually flattening of these rolls. In the experiment the height reduction is an adjusted but not controlled size.

b) The roll bending due to the calculated rolling force is an a priori estimated value. In the present rolling case the deflection line is a little smaller than the measured bending in experiment.

c) The axis of the roll is fully constrained. Thus only the half of elastic deformation capacity of the working roll is in effect.

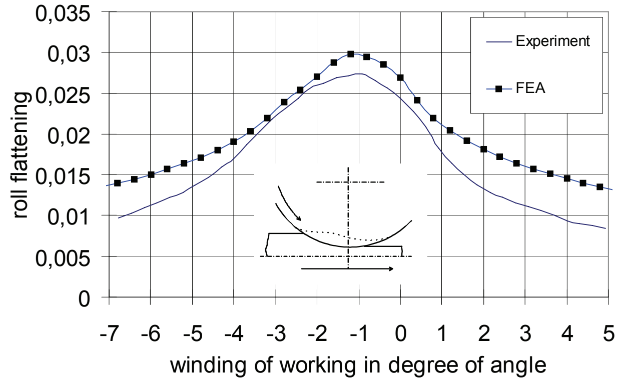

Fig. 9. Comparison between experiment and FEA of elastic deformation of the outline in rolling direction

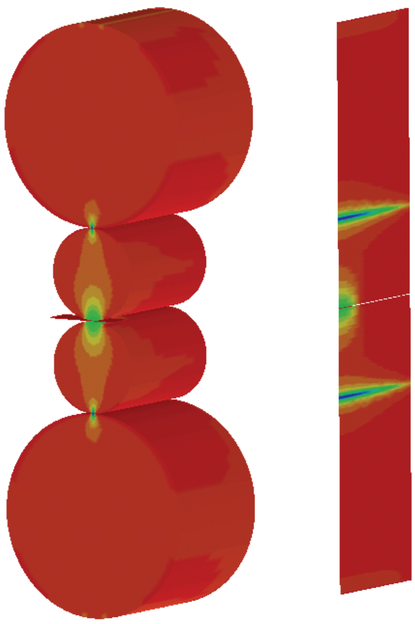

Fig. 10. Finite Element model considering back-up rolls

As an conclusion, the calculated elastic deformation is higher, because the whole mechanical reaction of the roll stand is reduced to the flattening between the working roll and the strip.

At the moment, research work is going on to enhance the elastic program module to a multi body system (Figure 10). Then it will be possible to include the elastic behaviour of the back up rolls in the simulation. First results show that the simulation time is not necessarily influenced by this. The increasing number of elements is not decisive in linear elastic models. The consideration of contact only leads to a small non-linearity due to the small change during the deformation simulation.

Modelling of the tools as elastic parts is not limited to rolling processes and ought to be combined with closed die forging or other precision forming technologies, in the future.

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SPRĘŻYSTE ODKSZTAŁCENIE NARZĘDZIA W PROCESIE WALCOWANIA NA ZIMNO

Streszczenie

Wprowadzenie walca jako obiektu sprężystego ma istotne znaczenie dla dokładności symulacji procesu walcowania na zimno. Schemat płynięcia odkształcanego materiału w kotlinie walcowniczej zależy w znacznym stopniu od sprężystego odkształcenia walca. Olbrzymi wzrost efektywności komputerów w ostatnich latach umożliwił realistyczne uwzględnienie tej zależności w numerycznych symulacjach. W niniejszym artykule pokazano symulacje sprężystego odkształcenie walca roboczego i omówiono jego wpływ na kształt odwalcowanej taśmy.

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