Description of the contact between a deterministic anisotropic tool surface and a workpiece subjected to plastic deformation

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Abstract: The finite element method offers an opportunity to obtain important information by simulating metal-forming processes. The description of the tool–workpiece interaction still remains a critical issue. The aim of this paper is to describe the contact between a deterministic anisotropic tool surface (grooved) and a workpiece. This is done by means of an existing contact processor and a friction law that has been conceived to describe sliding friction. This compromise solution of describing a contact state near to sticking by means of a law created for sliding friction is investigated. The results obtained using a macrogeometric model of the grooved surface are compared to those achieved by an idealized smooth surface and different friction coefficients. Next, an anisotropic model is introduced and calibrated using the inverse method based on the ring upsetting test for a hot-worked steel.

Keywords: metal forming, finite element method (FEM), contact boundary conditions, anisotropic surface

NOTATION

a, b, c	numerical parameters
C	the critical value of t, below which sticking is considered
C_1	Coulomb friction tensor
f_f	tangential friction force
f_n	normal force
t	actual tangential relative sliding velocity
Δd	relative reduction of the internal diameter (%)
Δh	relative height reduction (%)
ΔD	relative enlargement of the external diameter (%)
μ	friction coefficient
θ	angle between relative sliding velocity and the main direction of plane orthotropy

1 INTRODUCTION

In metal forming, the contact state between the process partners (tools and workpiece) is a very important factor in the eventual part quality and the tool life. Most of the processes require an enhancement of contact by proper lubrication. This leads to small friction forces applied to the working surfaces of the tool and thus to lower wear, which in turn has beneficial influences on both the part quality and on the production costs. However, there are cases that require a certain value of the friction forces for the process to take place. To the latter category belong the rolling processes, where the deformation forces are transmitted through the contact between the rolls and stock.

For certain geometric ratios of the working zone extremely rough tool surfaces might be required. In the case of axial feed bar rolling, Voelkner *et al.* [**1**] employ grooved active rolls in order to make the workpiece rotate. Here, the contact state can be regarded as ‘sticking’ rather than ‘sliding’. A reliable description of this type of contact by the finite element method (FEM) is difficult. This paper presents an approach to the description of this phenomenon by the inverse method.

The most common way of describing the frictional contact between tools and workpiece is by means of a friction coefficient, which relates the tangential friction force/stress and the normal force/stress. Models commonly implemented in FEM programs are the Amonton–Coulomb model and the constant shear model [**2**]. However, a better approach is given by the normal pressure-dependent model of Bay and Wanheim [**3**]. Most of the commercially available FEM packages allow the user to define his or her own friction model to compute a local friction coefficient. The friction model is implemented in FEM by means of a friction law, which explicitly or implicitly computes the concentrated friction forces, as presented by Zhong [**4**].

In the following, the MARC* program is employed to

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*MARC is a product of MARC Analysis Research Corporation, Palo Alto, California, USA.

perform the analysis. Here, the effect of friction on the finite element (FE) mesh of the deformed body is taken into account by the application of distributed loads (computed by one or another of the above-mentioned friction models). The need to distinguish between slip or stick state at a node, which occurs at small relative velocities of the contact partners, has led to the introduction of a smoothed step function:

$$f_{\mathrm{f}} = -\mu f_{\mathrm{n}} \frac{2}{\pi} \operatorname{atan}\left(\frac{t}{C}\right) \quad (1)$$

where f_{f} is the tangential friction force to be applied, f_{n} is the normal force, μ is the friction coefficient, t is the actual tangential relative sliding velocity and C is a critical value of this velocity, below which sticking is assumed (a typical value for C is 5 per cent of the averaged t). The same friction law is employed for the tangential friction stress in relation to the shear flow stress, which makes both models similar from the implementation point of view.

The aim of this paper is to describe the contact between a deterministic anisotropic tool surface and the workpiece, which can hardly be described as a sliding contact. This is done by means of an existing contact processor and friction law—actually conceived to describe sliding friction. This compromise solution of describing a contact state near to sticking by means of a law created for sliding friction is investigated in the following by comparing a macrogeometric model of the grooved surface with an idealized plane model of the same. Next, an anisotropic model will be introduced and calibrated by the inverse method based on ring upsetting tests of the type described by Male and Cockcroft [**5**] for the hot-working of steel.

2 ANALYSIS OF A MACROGEOMETRIC MODEL OF THE TOOL SURFACE

The process of axial feed bar rolling [**1**] is performed in two phases. The active rollers (Fig. 1) drive the workpiece in rotation. A radial feed phase is performed up to the prescribed depth, followed by an axial feed phase which thins the bar to a desired length. One surface of the rolls is grooved in the radial direction to enhance the transmission of the working moment to the workpiece. The grooves have a periodic reference profile of triangular shape with a tip angle of 60°. The groove height is about 0.5 mm. The radius at the tip of the groove, which is subject to wear, has been assumed to be 0.05 mm.

The contact between the grooved tool and the workpiece (steel at hot-working temperature) is calibrated by ring upsetting [**5**], which is a sensitive test method. Here, the most important quantitative parameter is the inner diameter of the ring, which decreases with an increase in friction coefficient. However, the material flow can be an indicator of the quality of the contact. A simple test is simulated by two means.

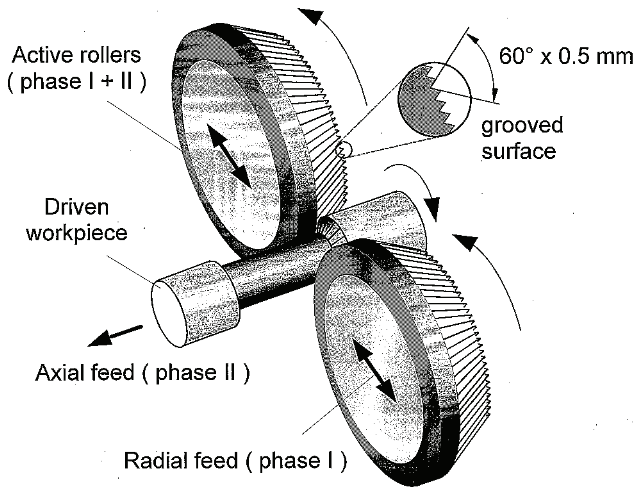

Fig. 1 Schematic representation of the axial feed bar rolling. In detail, the profile of the grooves on the front surface of the roller

Firstly, the grooved tool surfaces are modelled as a macroscopic feature (Figs 2a to d). The model is axisymmetric, which means that the grooves are circular. A friction coefficient of $\mu = 0.3$ has been assumed. A quarter of the ring is meshed with 700 axisymmetric linear quad elements and the automatic remeshing facility of MARC/Autoforge is utilized. An elastoplastic material law describes the behaviour of steel at a strain rate of $1.6\,\mathrm{s}^{-1}$. An isothermal hypothesis has been considered, since the influence of the temperature on the material law is only of secondary importance in the problem being analysed. Material markers (lines) retrieve the material flow during the phases of the upsetting process presented in Figs 2a to d. The indentation process of the grooves in the workpiece material can be observed to cause the affected material layer to stick on to the tools. Even two or three of these grooves are able to hold the workpiece surface layer. Thus, a more intense plastic deformation takes place in the layers from underneath. A more pronounced sticking effect will be produced by a larger number of grooves in contact.

The use of a detailed modelling technique of such deterministic macroscopic features of the tool is not feasible, especially using larger three-dimensional models, due to the required degree of local mesh refinement and to the necessity of automatic remeshing. In the following, the tool surfaces will be modelled as smooth, and the almost sticking contact due to the grooves will be taken into account by increased concentrated friction forces.

In this respect, for the same ring model, the tool surfaces are plane and the Coulomb friction model is applied. The results of the simulation (Fig. 3) can be quantified by representing the relative inner diameter change Δd versus the relative height reduction Δh of the ring. It can be seen that the results obtained by using a grooved model of the die surface are matched by the ones obtained using a plane die in the case of high friction coefficients. Similar good agreement has been reached between the two models in

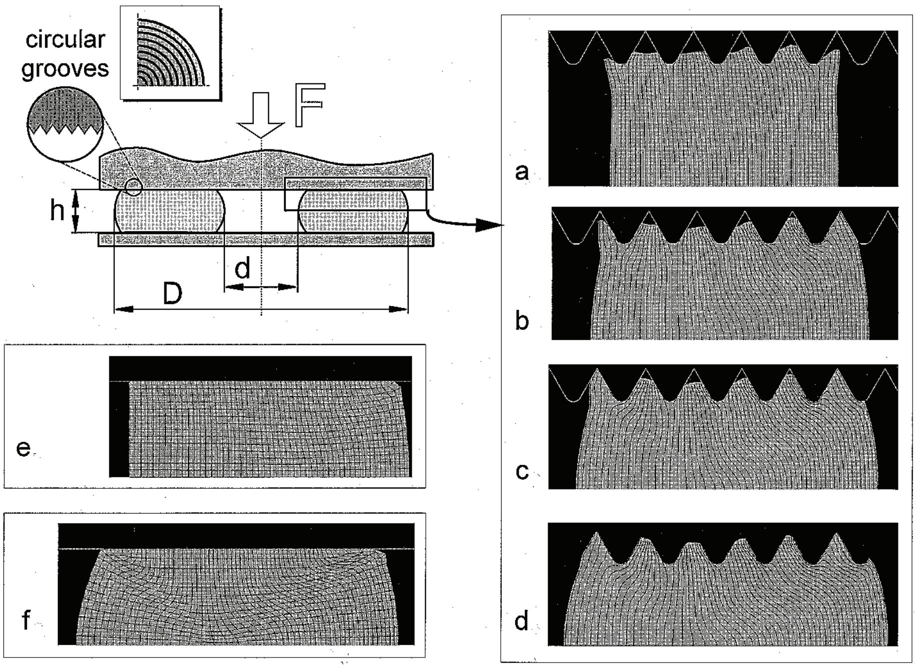

Fig. 2 Process scheme and simulation results regarding the material flow by upsetting of a ring between circularly grooved tools: (a)–(d) subsequent stages when grooved die geometry is modelled, (d)–(f) deformation pattern by 32 per cent height reduction, (d) grooved dies, (e) plane dies and $\mu = 0.2$, (f) plane dies and $\mu = 2.5$

terms of reaction forces on the rigid surfaces. It is not in the spirit of traditional tribology, which deals with sliding contact, to employ friction coefficients larger than one, but in this case the only effect of using friction coefficients of $\mu = 1.8$ or 2.5 is that the concentrated friction forces applied to nodes are higher. In the real case such high forces due to the grooves also hold the surface layer of the workpiece in the tangential direction.

Qualitative comparison of the two models can be made regarding the material flow at a certain stage in the process. The flow patterns at a 32 per cent height reduction are represented in Fig. 2d for the grooved die model and in Figs 2e

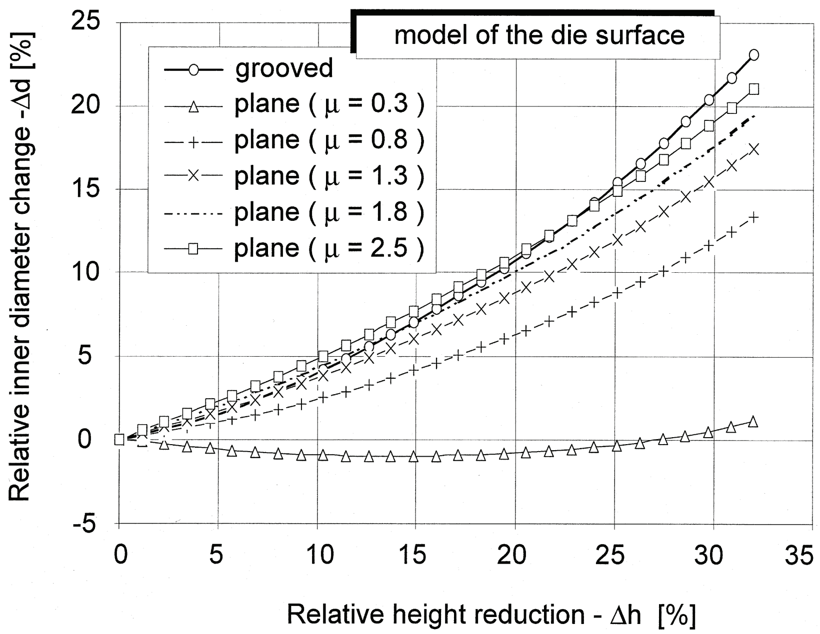

Fig. 3 Simulation results obtained by modelling the die grooves and by a plane die model. Changes of inner diameter versus height reduction

and f for the plane die model with friction coefficients of $\mu = 0.2$ and 2.5 respectively. By using $\mu = 0.2$ on the plane die, the friction is of the sliding type and the flow pattern is very dissimilar to the one obtained with the grooved die. Good resemblance of the flow pattern can be observed in Figs 2d and f. The 'sticking' of the workpiece surface layer to the smooth tool is reproduced well by the high friction coefficient.

3 DESCRIPTION OF CONTACT WITH AN ANISOTROPIC SURFACE

The isotropic constitutive relation of Coulomb sliding friction is based on colinearity of the relative velocity ($\boldsymbol{t}$) and friction force ($\boldsymbol{f}_f$) vectors. Moreover, from the algorithmic implementation point of view, the frictional forces in sliding are assumed to act in the same directions as the contact tangential forces prior to sliding [**6**]. A general anisotropic friction model has been proposed by Zmitrowicz [**7**], and couples the relative velocity ($\boldsymbol{t}$) and friction force ($\boldsymbol{f}_f$) vectors with a linear relation:

$$\boldsymbol{f}_f = |\boldsymbol{f}_n| C_1 \boldsymbol{t} \tag{2}$$

where C_1 (the Coulomb friction tensor) is a non-singular second-order tensor, defined in the space that is the tensor product of the vector spaces of the vectors $\boldsymbol{f}_f$ and $\boldsymbol{t}$. Generally the vectors $\boldsymbol{f}_f$ and $\boldsymbol{t}$ are not colinear. They have different norms and directions. Isotropy is obtained as a particular case when C_1 is the unit tensor multiplied by $-\mu$. The implementation of such a model is relatively impractical, due to the difficulties of evaluating the Coulomb friction tensor (C_1) components and due to the additional convergence uncertainty involved.

In the present case, the tooling surface possesses a deterministic orthotropic anisotropy, given by the direction of the macroscopic grooves and the direction perpendicular to them. The microscopic characterization of the surface is stochastically isotropic, but the effects of roughness are not the primary aim of this study. Thus, two principal directions can be identified on a contact patch of the tool (Fig. 4). Direction {1} corresponds to the grooving and is the most favourable sliding direction. A practical approach to anisotropic contact is taken in the following by defining a local friction coefficient value. This is computed based on the angle between the relative velocity vector ($\boldsymbol{t}$) and the principal direction of surface orthotropy {1}. A minimal friction coefficient value will be assigned to the nodes that have a relative velocity in the direction {1}. A maximum value will be assigned to the nodes tending to move in the direction {2}. For the nodes that have a relative tangential velocity direction between {1} and {2} the values of the friction coefficient are computed by a function $\mu = f(\theta)$. The function $f(\theta)$ should be continuous, differentiable and not have singular points. The function should permit a variation of the extreme values and of the slope. A function with three

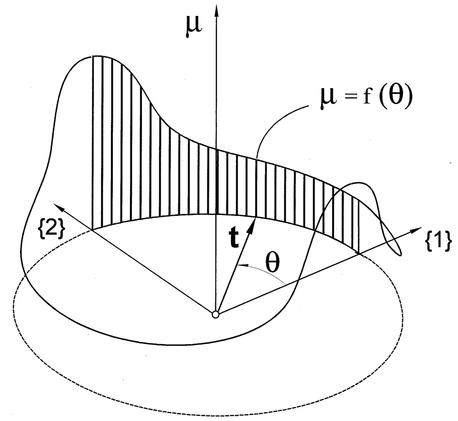

Fig. 4 Graphical representation of the local friction coefficient function

parameters defined on the interval $[-\pi/2, \pi/2]$ has been investigated:

$$\mu = \frac{1}{a\theta^2 + b} + c \tag{3}$$

The friction forces act in the opposite direction to the relative velocity (t) and are weighted by the local friction coefficient. The applicability of this model is limited by the need to correlate the local coordinate system of each contact patch which represents the rigid surface of the tool with the principal direction of surface orthotropy {1}.

4 CALIBRATION OF THE MODEL

The model described earlier has been applied by means of the user subroutine UFRIC in the MARC program. The inverse method is employed to determine the model parameters a, b and c [equation (3)]. Upsetting experiments (Fig. 5a) have been carried out on Ck45 (a steel grade according to DIN 17200) steel rings with the dimension ratio (D_0:d_0:h_0 of 20:10:7 mm) according to Burgdorf [**8**]. The plane tools are machined with straight and parallel grooves with the same groove profile of $60^\circ \times 0.5$ mm, as in the case presented in Section 2 where the grooving was circular, in order to describe isotropic friction conditions. Tools are lubricated with a mixture of graphite and MoS_2. The test rings were heated scale-free to an oven temperature of 1000 °C. Two indicators were observed: the internal diameter reduction Δd (%) and the external diameter enlargement ΔD (%). Both are measured in parallel and in the transverse direction to the grooves, for different upsetting heights.

Finite element simulation of the process is performed using an elastic–plastic isothermal material law. An eighth part of the ring is modelled by 1890 linear hexahedron elements in a constant dilatation formulation. Due to the sticking character the nodes at the edge of the contact are not expected to show large displacements. Therefore, they are

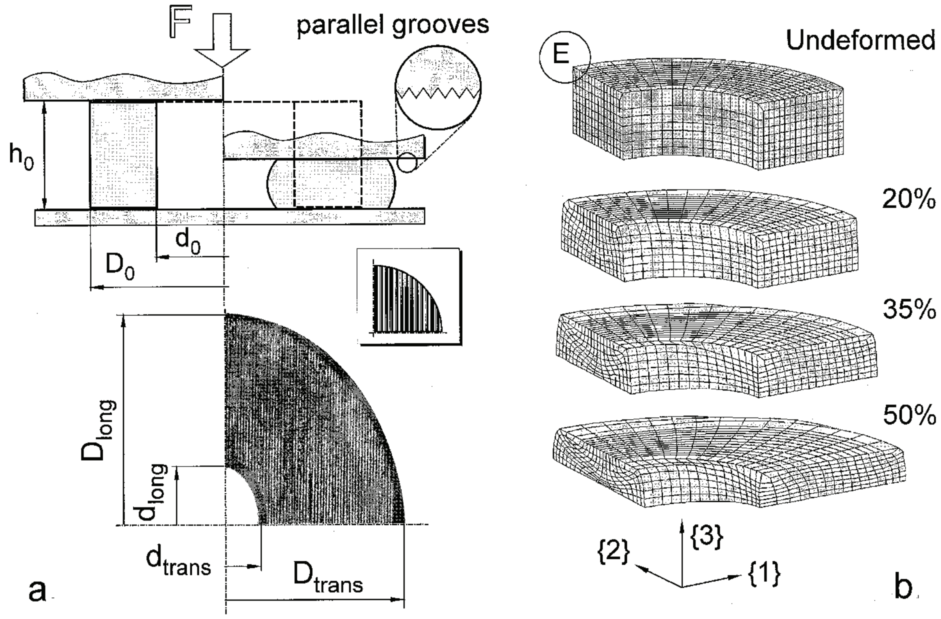

Fig. 5 Model of the ring upsetting process: (a) schematic representation and experimental measured results, (b) FEM model, before and after 20, 35 and 50 per cent upsetting

shared by four elements as in detail E of Fig. 5b, in order to avoid the complete degeneration of an element in the early steps.

The calibration of the model is performed in an iterative process. Different graphics of the model function [equation (3)] are presented in Fig. 6. The best fit is achieved by the parameter combination: $a/b/c = 6.6/1.15/0.15$. In addition to good quantitative agreement of the computed diameter changes (Fig. 7) with the experiment, a good qualitative description of the deformation process has been achieved. The sticking character of the contact observed experimentally is also modelled by simulation. The friction coefficient takes values between 0.21 and 1.02, which is in agreement with the results presented in Section 2.

The contact modelling results obtained in this calibration using plane dies can be extrapolated to three-dimensional

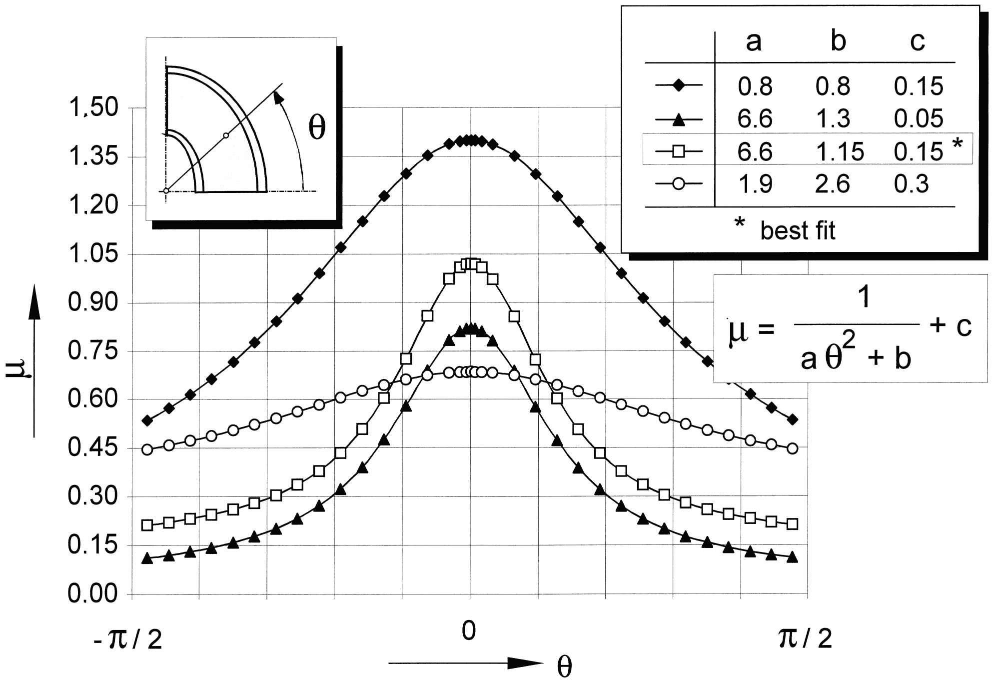

Fig. 6 Variation of the friction coefficient with the orientation angle of the relative velocity vector at different parameter combinations

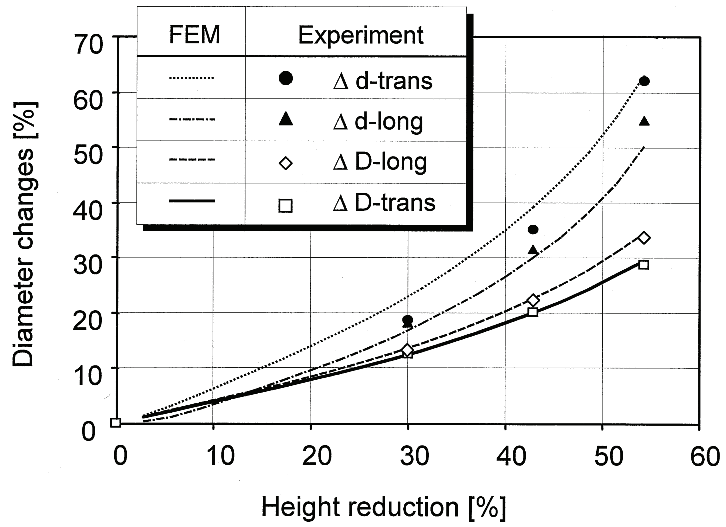

Fig. 7 Comparison between computed and experimental results (ring upsetting, specimen geometry according to Burgdorf [**8**], Ck45 steel at 1000 °C, dies with parallel grooves 60° × 0.5 mm) regarding the variation of the ring diameters with the height reduction

grooved tool surfaces by axial feed bar rolling [**9**], where the curvature radius of the roller (Fig. 1) is about 300 times larger than the groove dimension and the contact patches are almost plane. This model can be modified and calibrated accordingly for similar processes with different macrogeometries of the surface, thus enabling an anisotropic contact description to be made without the need to interfere at the contact processor level.

5 CONCLUSIONS

A description of the contact between tools and workpiece in a metal-forming process has been presented. The character of the contact is near to sticking due to macroscopic grooving of the tools in one direction (orthotropy), which makes the surface roughness (at the microscopic level) of only secondary importance. A rigorous analysis of such processes based on geometrical descriptions of the macrofeatures is impractical.

An approach using smooth tool surfaces and the classic Coulomb friction model is introduced and compared by simulation using the FEM code MARC. The requirement to employ high values for the friction coefficient has been dictated by the necessity to impose tangential contact forces high enough to simulate sticking. A further development is the anisotropic friction description by means of a local friction coefficient conditioned by the angle between the relative displacement velocity and the principal direction of surface orthotropy.

The proposed variation function of the friction coefficient has been calibrated by the inverse method on ring upsetting tests. Good agreement under qualitative and quantitative aspects has been achieved.

This kind of description of contact problems has limited applicability, but is easy to extrapolate and calibrate. Application to more complex rolling processes is envisaged. New developments in the direction of defining a slip/stick status based on the tangential displacement magnitude [**10**] promise a more stable and accurate contact description, but for the case analysed here have limited applicability. However, they will still be subject to calibration.

A more detailed analysis of the anisotropic contact deserves further study such as the implementation of the anisotropic friction tensor model [**7**] and the development of a determination methodology for its components. Such efforts can only be motivated by a correspondingly substantial application area. Developments in the rolling technology of deep-drawing sheets with surface texture might provide an impetus in this direction.

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