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A FINITE ELEMENT SOLUTION OF STRIP ROLLING

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SUMMARY

In this paper a numerical solution of strip rolling based on finite element method is presented. The material behavior in the form of a stress-strain curve obtained from a plane-strain compression test and measured interfacial velocities as prescribed boundary conditions are used as input data to the numerical model of strip rolling. Numerical results such as distributions of roll pressure, frictional stress, and coefficient of friction in the contact region are presented.

INTRODUCTION

Analysis of strip rolling must be able to provide the pressure distribution in the roll gap, the roll force and torque with accuracy and consistency. Several analyses have been published in the literature. The theory of homogeneous deformation suggested by von Karman (1) was based on simplified equilibrium of forces acting on a slab element in the deformation zone of strip. Orowan (2) discarded the assumption of homogeneous deformation and developed a theory of inhomogeneous deformation. The differential equation for slab element was derived under various assumptions and approximations by Nadai (3), Bland and Ford (4) and Sims (5).

A slip-line field solution for hot rolling was presented by Alexander (6), and further slip-line field solutions for cold rolling were suggested by others (7,8). Local stress, velocity distribution, and pressure distribution can be determined by this method. An upper bound method was proposed for the analysis of rolling by Avitzur (9). It provides a good estimate of upper limits of the deformation force but cannot give details of local stress and strain distrubutions. In all of the above mentioned solution procedures, inadequate information on the frictional conditions existing at the interface precludes quantitative predictions of an actual process.

Finite element solutions are capable of providing better simulations of metal forming processes because realistic boundary conditions and elastic-plastic workhardening properties of workpiece can be taken into account. Zienkiewicz et al. (10) considered the rolled material to be rigid-viscoplastic and incompressible. Friction was simulated by introducing a thin layer of elements whose yield strength was assumed to depend on the product of the coefficient of friction and mean stress. Mori et al. (11) assumed the strip material to be rigid-plastic and used constant coefficient of friction along the strip-roll interface. Li and Kobayashi (12) also assumed the existence of rigid-plastic material and introduced a function of relative velocity to simulate the interface friction. Hwu and Lenard (13) considered a similar model for studying the effect of roll deformation.

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The first elastic-plastic finite element analysis for skin-pass rolling was presented by Tamano et al.(14). Liu et al. (15) applied the friction-layer technique which consisted of an extra layer of elements on each surface of the workpiece on which friction acted. Many others developed good programs to solve large-strain plastic deformation processes. To obtain solutions, the analysts were forced to employ a friction model such as a Coulomb condition or a constant shear stress factor, despite indications that none of the existing models is truly representative of actual physical conditions in metal forming.

Experimental verification of frictional coefficient in the roll gap can be found in the technical literature. In one of the earlier works, van Rooyen and Backofen (16) used two pin-type transducers imbedded in the roll to measure normal pressure and interfacial shear stress (frictional stress) simultaneously. Al-Salehi et al. (17) used a similar technique to that of van Rooyen and Backofen. Lim and Lenard (18) conducted experiments to measure the effect of roll pressure, roll speed on the magnitude and variation of the coefficient of friction in the roll gap. In all of these experiments, the variation of coefficient of friction in the roll gap was very pronounced.

Because of lack of knowledge about the nature of friction at the interface, Rao et al. (19,20) used a measured velocity profile to the model of strip drawing. Rao et al. (21) also used measured velocity as an input to the numerical analysis of Steckel rolling process. In the present work, a similar approach has been adopted in solving strip rolling problem. Interfacial velocities have been measured in strip rolling using an inclined line technique. Plane-strain compression test has been performed to obtain the stress-strain behavior of work material. Such measured data have been fed as input to the finite element model of strip rolling process. The computational code used here is based on the finite element program, EPAFRIC (22), together with some modifications to allow velocity boundary condition instead of Coulomb friction.

EXPERIMENTAL PROCEDURES

Experimental set-up and materials

Rolling experiments were carried out in the research laboratory at Inland Steel. The rolls are made of hardened steel of 510mm in diameter and 400mm in length. Rolls were shot blasted to have uniform matte finish of R.M.S. roughness of about 0.75 µm. They have about 94 Shore C-type hardness. The experimental set-up is shown in Fig. 1. Rolling experiments were carried out on a mild steel strip of 250mm in width and 2.3mm in thickness. The STANAT rolling mill can control the roll gap, roll speed and has a device for monitoring roll separating force. A specific case, reduction of 19.8% with kerosene as lubricant, was used in the analysis.

Velocity measurements

Straight line inclined to the direction of rolling was scribed on the surface of the undeformed strip. As the strip entered the roll-contact region, the surface line became curved as the strip exited there from the line became straight again. This behavior is shown in Fig. 2 schematically. The curvature of the line in the roll contact region reflects the fact that the material travels faster as it progresses through the roll due to reduction in thickness. The emergence of a straight line from the roll exit supports the assumption of steady state conditions in which all the points on the line have experienced the same displacement history. It is also consistent with the assumption of plane strain. It can be easily proven that the slope of an inclined line at any position on it is proportional to the corresponding horizontal component of velocity.

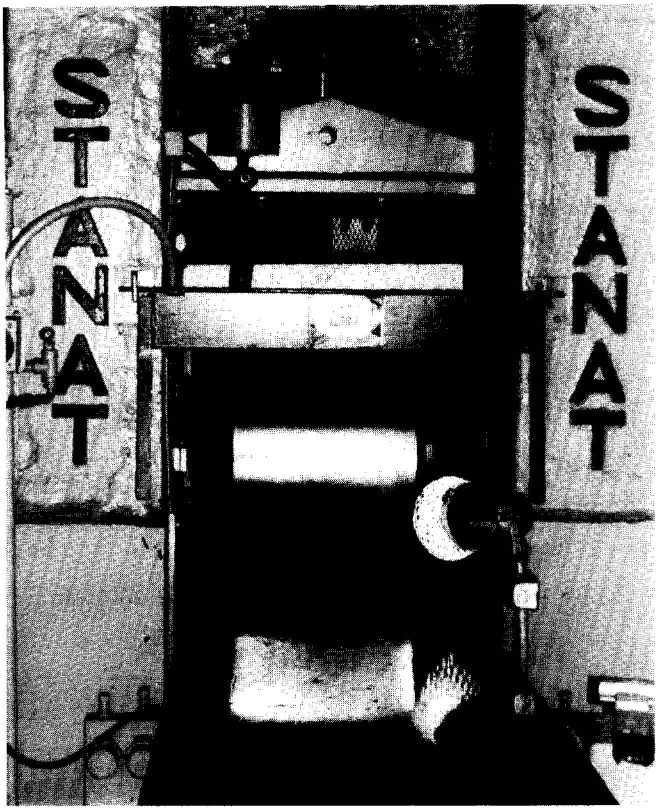


Fig. 1. Experimental set-up

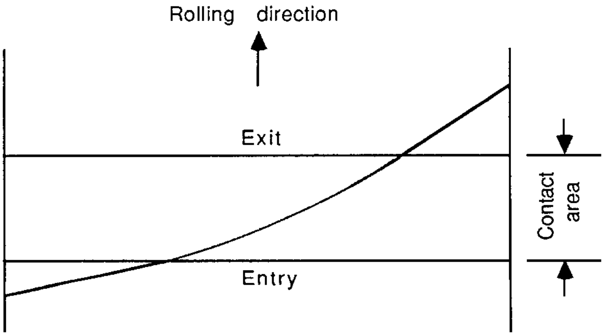


Fig. 2. Schematic diagram of inclined line technique

$V_i/m_i = V_e/m_e$

$V_i = V_e(m_i)/m_e$

where V_e = Exit velocity

V_i = Interface velocity at any position "i" in the contact region.

m_e = Slope of the inclined line at the exit.

m_i = Slope of the curved line at any position "i" in the contact region.

Knowing V_e, m_e, and m_i, V_i can be found.

An inclined line was printed on a mild steel strip of 250mm wide and 2.3mm thick and reduced by 19.8% in thickness by the strip rolling process. The experiment was conducted under lubricated conditions with kerosene. The analysis of obtaining velocity in the contact region was done after the process. The displacement values within the contact region were read from the magnified photographs of the contact region and then were fitted to an equation. By differentiating the equation, the interfacial velocities in x direction were obtained and shown in Fig. 3 and also presented in the form of an equation as

$$V_i = .8036 + .0318x - .0079x^2 + .00213x^3 - .00023x^4 + .0000087x^5 \quad (1)$$

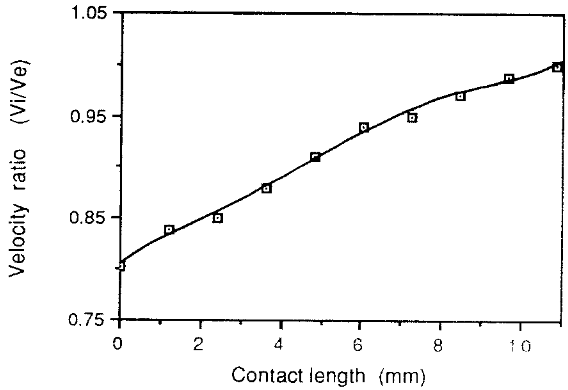


Fig. 3. Measured velocity profile

This data was used as a prescribed boundary to the finite-element analysis of strip rolling along with the stress-strain equation obtained from a plane-strain compression test as described below.

Plane-strain compression test

In order to characterize the material behavior in the form of a stress-strain curve, a plane-strain compression test was conducted as rolling conditions are similar to this test. The dies were made of tool steel. Appropriate dimensions of dies and workpiece were maintained to ensure the plane-strain condition. The effective stress-strain relation for mild steel strip was approximated by least square method as

$$\bar{\sigma} = 778\,\bar{\varepsilon}^{0.303} \quad \text{(MPa)} \tag{2}$$

where $\bar{\sigma}$ is the effective stress and $\bar{\varepsilon}$ is the effective strain. The elastic constants employed in the analysis were Young's modulus, $E = 203$ Gpa, and Poisson's ratio, $\nu = 0.29$. The theoretical and computational procedures are described below.

THEORETICAL AND COMPUTATIONAL PROCEDURES

The analysis presented here is based on the finite-element analysis program, EPAFRIC (22), together with certain modifications to it which allow the solution of strip rolling. The theoretical basis of the program is a rate formulation of isotropic work-hardening-plastic material behavior in which the total strain rate is the sum of the elastic and plastic parts. Plastic flow is assumed to be incompressible. Jaumann's stress rates for isotropic hardening materials are applied to ensure material frame indifference of the constitutive equations. The equations obtained by eliminating stress rate from the constitutive equations and from the rate form of the equations of equilibrium determine the instantaneous spatial variation of the velocity field. The equivalent equations for instantaneous displacement increments are solved by employing a finite-element discretization of the body based on constant-strain-increment triangles.

The problem analyzed is that of a strip of metal being reduced in a rolling process. The strip is assumed to be sufficiently wide in relation to its thicnkess that its deformation can be adequately modeled by a plane-strain solution. Typically, in the strip rolling process, plastic flow is confined to a region more or less between the rolls. Material that has not yet reached the contact region and the material that has passed through the rolls are normally subject to stress below the flow stress and therefore such material deforms purely elastically.

In order to carry out a finite element solution with a manageable number of elements the strip is truncated in length as shown in Fig. 4. The solution procedure begins with the end of the strip close to the roll exit and is terminated well before the strip end reaches the roll entry. Thus the material initially is assumed to be at rest, stress free, and of uniform hardness throughout. Only, the steady-state conditions, in which all the material initially under the rolls has passed through it, are presented in the discussion. Symmetry of the strip with respect to its center plane allows us to consider in detail only half of the strip. The strip region analyzed is shown in Fig. 4 together with the applied incremental boundary conditions at a generic stage of rolling. The measured horizontal velocities are prescribed along the roll-work interface. ΔU_x and ΔU_y are displacement increments and ΔF_x and ΔF_y are force increments which are zero on free surface.

The initial configuration of the strip including finite element mesh is shown in Fig. 5(a). The mesh consists of a grid of quadrilaterals of 40 in each of the four rows. Each quadrilateral is divided into four cross-triangle elements and thus there are 640 elements altogether. Becuase of the symmetry about the strip center plane, only half of the strip is considered for analysis as shown in

Fig. 5(a). The quadrilaterals closer to the strip surface were made thinner than those near the center plane of the strip to improve modeling of the higher gradients of mechanical variables near the surface.

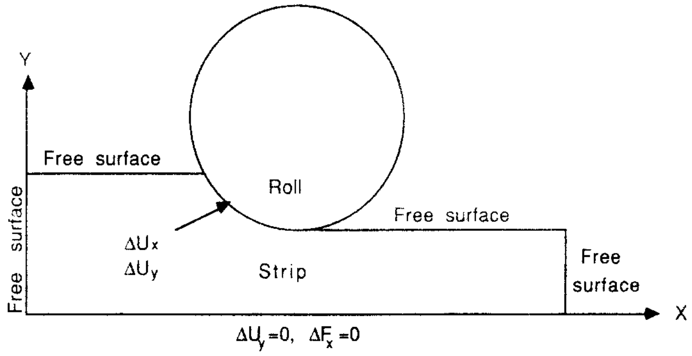
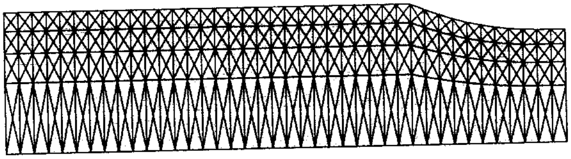
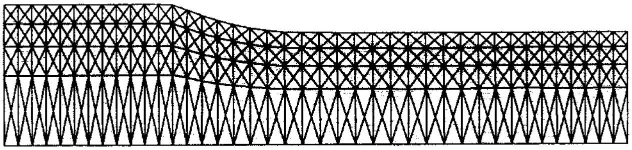


Fig. 4. Strip rolling boundary conditions



(a) Initial mesh configuration



(b) Deformed mesh configuration

Fig. 5. Finite element discretization

Solution to the problem was obtained by incrementing the displacement of the leading end of the strip and concurrently applying increments to the roll-strip interface according to the velocity profile derived from the experiment. The solution was continued until somewhat beyond the stage when all the material initially under the roll emerged from it. Material leaving the roll at this stage has experienced essentially the complete deformation change associated with the strip rolling process. The configuration of the deformed strip after reaching steady-state condition is shown in Fig. 5(b). The deformation is consistent with the physical understanding of the process. The results are discussed in the following section.

RESULTS AND DISCUSSION

The variations of normal pressure and shear stress (frictional stress) in the roll gap are shown in Fig. 6. The shear stress changes its direction somewhere near the mid-point in the contact region. The point where the shear stress is zero is assumed to be close to the neutral point. There is no relative movement between strip and roll at the neutral point. The negative shear stress variation (see Fig. 6) is shown from entry to the neutral point. This is in the direction of roll velocity which helps in pulling the material into the roll gap. The positive shear stress variation is shown from the neutral point to the exit. These variations are consistent with the rolling theory. However, some researchers suggested that there is a central neutral zone of metal which moves with the roll surface (8,23). In other words, the change in the direction of shear stress occurs over a small wedge shaped zone of a rigid material. There is no evidence of such phenomenon in our research findings.

The variation of normal pressure in the roll gap is also shown in Fig. 6. According to the rolling theory, the pressure peak occurs at the neutral point. The peak pressure in the case of mild steel for a reduction of 19.8% is about 930 Mpa. Thus, the pressure reaches its maximum somewhere between the neutral point and the exit, but not exactly at the neutral point. As mentioned in the introduction, Lim and Lenard (18) experimentally determined the variations of pressure and shear stress in the roll gap for several reductions and speeds for aluminum. They also observed that the neutral point does not necessarily coincides with the peak pressure. In addition, they obtained several different distributions such as a single peak, double peak, and flat region in the mid region of contact for several processing conditions in strip rolling.

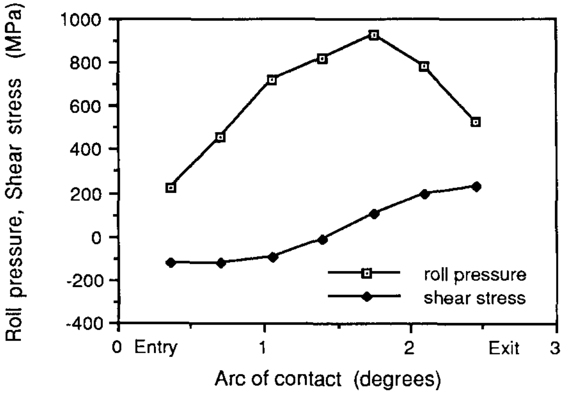


Fig. 6. Variations of normal pressure and shear stress

By taking the ratio of shear stress to normal pressure, the variation of the coefficient of friciton in the contact region can be obtained as shown in Fig. 7. It is evident that the coefficient of friction in the roll gap does not remain constant. The experimental results of Lim and Lenard (18) can not be compared directly with the present numerical predictions because of different processing conditions. However, the general trend of the coefficient of friction variation favorably compares well with their experimental findings. As shown in Fig. 7, the coefficient of friction varies from 0.02 to 0.54 for a case of 19.8% reduction of mild steel strip under lubricated conditions. The coefficient of friction values are high at both the entry and exit and almost zero at the neutral point.

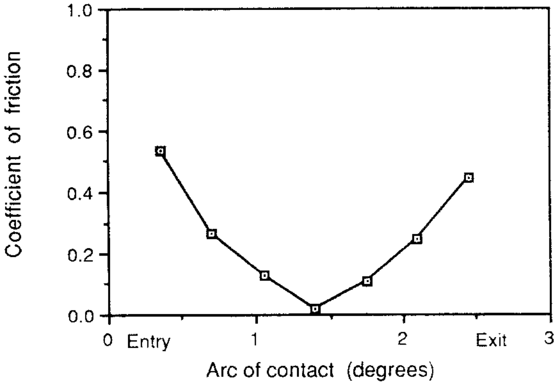


Fig. 7. Variation of coefficient of friction

The shape of the deformed strip, the regions of plastic deformation, the character of predicted stress distributions and other features of the solution are consistent with our understanding of strip rolling process. Currently, the work is in progress to investigate the effect of several other processing parameters on friction and finally, we hope to develop a new friction model.

CONCLUSIONS

Instead of assuming an unrealistic model of a constant coefficient of friction along the roll-work interface in the analysis of strip rolling, measured velocities were employed. Finite element solution predicted distributions of pressure, frictional stress, and coefficient of friction in the roll gap. These preliminary results are very encouraging and in general agreement with the recent findings of others. Now the work is being continued to refine the velocity measurements further so that comparisons of roll separating force can be made for several cases. Since friction has direct influence on the product quality, the new experimental and computational procedures discussed here are very useful in order to gain better understanding of the fricitonal interactions in metal forming.

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