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Specific Pressure in Steel Rod Rolling with Grooves

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In the design of roll stands for use in grooved steel rod rolling, the contact pressure between the rolls and the incoming workpiece is very important. This value can be estimated with the help of a number of analytical and semiempirical models described in the published scientific and technical literature. In this study, the possibility of using numerical simulation in determining the contact pressure during the rolling of a round bar with oval grooves is analyzed. The results of the numerical analyses are then compared with those of two other modified analytical models.

Keywords FEM analysis, groove profile, hot rolling,

1. Introduction

One manufacturing process through which a workpiece is plastically formed is known as rolling. Process parameters are mainly dependent on the final shape of the object to be produced (plate, sheet, etc.). If the final object is a bar or a section whose final shape is obtained after an intermediate pass sequence (e.g., grooved rolling), the configuration of the rolling process becomes relevant.

Generally speaking, complex interactions between several factors come into play: friction, contact pressure, diameter, roll speed, height reduction, temperature, groove design, gauging sequence, etc. A particularly important parameter at the stand design stage is the contact pressure exerted by the rolls on the incoming workpiece.

Contact pressure forecasting models made available in the scientific literature so far include analytical models by Ekelund and others (Ref 1, 2). Based on experimental observations and other considerations, these models have been modified in such a way as to obtain semiempirical evaluation models.

Due to technical difficulties, it is impossible to directly determine contact pressure levels during relevant experiments. However, based on torque and power level measurements, the pressure can be indirectly estimated with a tolerable degree of accuracy.

In this study, an extension of the finite element modeling (FEM) simulation is attempted to estimate specific contact pressure during metal forming processes using, as reference elements, the results of available theoretical and empirical relations.

2. Analytical Model

The Ekelund model is used to calculate the pressure (P_E) of the roll on the rolled material (Ref 1, 2). The rolling process relation is:

Table 1 Value of the coefficient (*c*)

Speed, υ, m/s	Coefficient (*c*)
Up to 6	1
6-10	0.8
10-15	0.65
15-20	0.6

$$P_E = \left[1 + \frac{1.6f\sqrt{R(H_0 - H_1)} - 1.2(H_0 - H_1)}{H_0 + H_1}\right]\left(K_c + \frac{2\eta\upsilon_m\sqrt{\frac{(H_0 - H_1)}{R}}}{H_0 + H_1}\right) \quad \text{(Eq 1)}$$

where

$$\sqrt{R(H_0 - H_1)}$$

is the length of the projected contact arc; R is the roll radius; H_0 and H_1 are the heights of the incoming and outgoing workpieces; f is the friction coefficient; υ_m is the mean rolling speed (mm/s) in the pass, which in a smooth rolling process equals the peripheral speed $\upsilon_m = \upsilon_r$ (This formula is applicable to speeds of up to 7 m/s); and η is the coefficient of plasticity of the rolled material (at temperatures greater than 800 °C) and is equal to:

$$\eta = 0.01 \times (14 - 0.001\ T)\ \text{kg s/mm}^2 \quad \text{(Eq 2)}$$

K_c is the yield stress, calculated by means of the formula:

$$K_c = (14 - 0.01\ T) \times (1.4 + \text{C} + \text{Mn} + 0.3\ \text{Cr})\ \text{kg/mm}^2 \quad \text{(Eq 3)}$$

In Eq 3, C, Mn, and Cr are the weight percent of carbon, manganese, and chromium in the steel, and T is the rolling temperature measured in °C (minimum value 700 °C).

When the rolling speed exceeds 6 m/s, the plasticity coefficient η (Ref 1) should be corrected by some factor (c) (Table 1) such that $\eta' = c\eta$, and this value should be substituted for η in Eq 1.

For grooved rolling processes, Wusatowski (Ref 1) suggests

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Table 2 Coefficient *m* for some type of pass

Type of pass	Coefficient (*m*)
Square with rounded edges	0.97-0.99
Square with acute edges	0.51
Diamond with acute edges	0.51
Diamond with rounded edges	0.56-0.58
Flat oval	0.67-0.75
Eliptic oval	0.785-0.82
Hexagonal	0.75
Round	0.785
Rounded oval	0.80-0.94

Table 3 Coefficient C_f for some types of pass

Type of pass	Coefficient (C_f)
Flat-flat	1.00
Round-oval	1.20
Diamond-square	1.20
Round-diamond	1.35
Oval-square	1.40

adopting Eq 1, though in association with a coefficient (*m*) to reduce the maximum height of the rolled material:

$$h_m = m\, h_{max}$$

In Table 2 the values of *m* for some type of pass are reported.

A model used in industry (Ref 3), developed on the Cook-McCrum studies (Ref 2), calculates the specific pressure using the following equation:

$$P_s = C_f K_c \left[1 + \frac{1.6 fL - 1.2(H_0 - H_1)}{(H_0 + H_1)} \right] C_1 C_2 C_3 \qquad \text{(Eq 4)}$$

where C_f is the additional friction coefficient, varying between 1.00 and 1.40, as a function of any one of the grooves reported in Table 3, K_c is the yield stress obtained using the relation proposed by Ekelund, f is the friction coefficient of the material being roll processed, H_0 is the height of incoming workpiece, H_1 is the height of outgoing workpiece, and L is the contact arc projection on the rolling direction. If the contact arc is 5-6°, it is generally equal to the chord—in this case, $L = \sqrt{R(H_0 - H_1)}$, and C_1 is the speed (m/s) effect correction coefficient based on the following values:

$C_1 = \sqrt[16]{V}$ for speed from 0 to 20m/s

$C_1 = \sqrt[8]{V}$ for speed from 20 to 100m/s

and C_2 is a coefficient that is a function of the contact arc determined by the following relation:

$$C_2 = 1.1 - \frac{0.3}{9.0} \left(\frac{2.0 \sqrt{\frac{\phi_{lav}}{2} (H_0 - H_1)}}{H_0 + H_1} - 1.0 \right) \qquad \text{(Eq 5)}$$

where ϕ_{lav} is the work diameter of the rolls and is calculated as follows:

$$\phi_{lav} = Diameter_{roll} + Roll\ Gap - \frac{Area_{\text{outgoing work-piece}}}{Width_{\text{outgoing work-piece}}} \qquad \text{(Eq 6)}$$

And finally, the coefficient C_3 in Eq 4 is a function of the slenderness of the rolled work-piece and is determined by the following function:

$$C_3 = 1 + \frac{0.1}{4.35} \left(\frac{L_0 + L_1}{H_0 + H_1} - 1.15 \right) \qquad \text{(Eq 7)}$$

where L_0 is the width of the incoming work-piece and L_1 is the width of the outgoing workpiece.

The area and maximum width of the incoming equivalent rectangle are equal to those of the incoming profile. In cases where the grooves are completely filled, the area and maximum width of the equivalent outgoing rectangle are equal to those of the outgoing profile.

In point of fact, the groove, due to its shape, size, worked material, temperature, and rolling speed, cannot be completely filled. This is why most models are suited only for calculating the approximate specific pressure values.

To determine the maximum width (W_{max}) for processes providing for incomplete filling, Shinokura-Takai (Ref 4) proposed the following relation:

$$W_{max} = W_i \left(1 + \gamma \frac{\sqrt{R_m (H_0 - H_1)}}{W_i + 0.5 H_i} \frac{A_h}{A_0} \right) \qquad \text{(Eq 8)}$$

where R_m is the mean roll radius, W_i is the maximum width of incoming workpiece, γ is the pass type-dependent correction coefficient (and it was posited at 0.83 for oval-round and for round-oval rolling passes (Ref 5). The above relation is applicable with a 4% error rate due to this value) and H_i is the maximum height of incoming workpiece.

The height values H_1 and H_0 are those of the equivalent rectangles in Fig. 1, which illustrates the methods used to determine the incoming and outgoing equivalent rectangles. The heights of these rectangles are, respectively:

$$H_1 = \frac{A_0 - A_S - A_h}{B_c} \qquad \text{(Eq 9)}$$

$$H_0 = \frac{A_0 - A_S}{B_c} \qquad \text{(Eq 10)}$$

Starting from the findings of Shinokura and Takai and Lee et al. (Ref 5, 6) developed an alternative method for determining the area of the outgoing workpiece in the cases of round-oval or oval-round sequences.

The area of a rolled object with an oval groove processed from a round bar can be calculated using the following relation:

$$A_{(oval)} = 4 \left[\int_0^{C_x} \sqrt{(R_1^2 - x^2)}\,dx - \left(R_1 - \frac{H_P}{2} \right) C_x + \int_{R_S - \frac{W_{max}}{2} + C_x}^{R_S} \sqrt{(R_S^2 - x^2)}\,dx \right] \qquad \text{(Eq 11)}$$

where C_x is the x-coordinate of the cross point of the

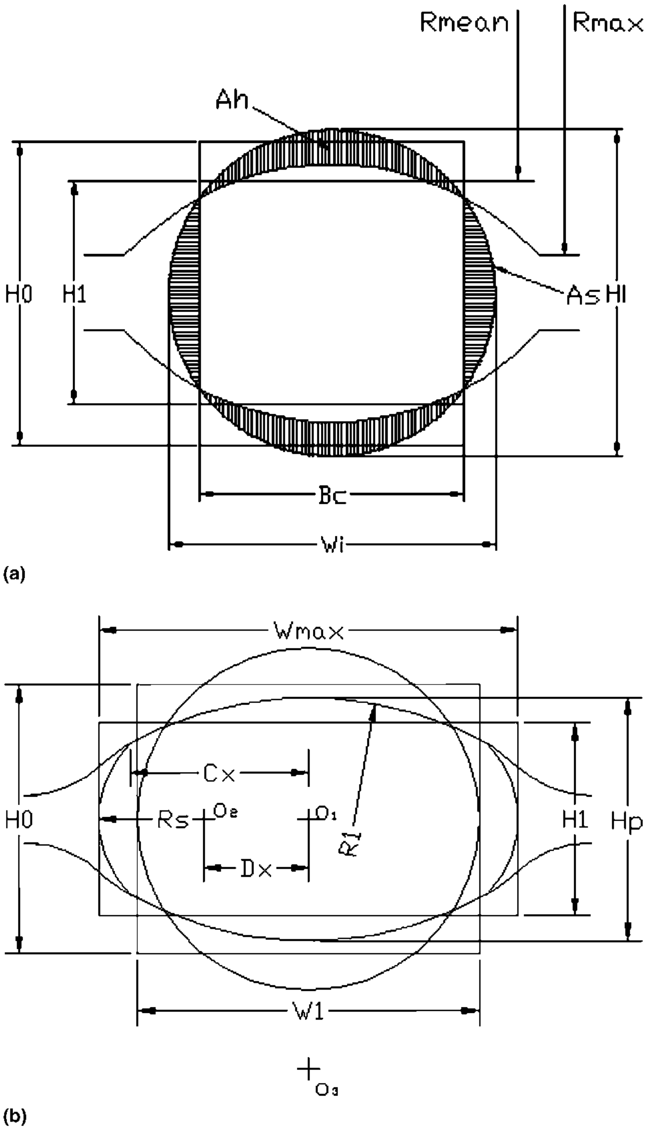

Fig. 1 Geometrical scheme of a roll groove: (a) Shinokura-Takai (Ref 4), (b) Lee, Choi, and Kim (Ref 5)

workpiece and roll groove, R_1 is the curvature radius of the oval groove, H_P is the pass height, D_x is the distance between the center of round groove and that of surface profile, and R_s is the radius of the workpiece surface profile used for any pass.

3. Analytical and FE Model Results

A three-dimensional numerical model was developed based on the Marc Autoforge calculation code (Ref 7) using linear solid tetrahedral elements with 8 nodes (Fig. 2). During the analysis, the roll was assumed to be a rotating rigid surface, and the rolling process was assumed to be carried out on C15 steel (0.15% C, 0.45% Mn) under isothermal conditions (1150 °C).

The diameter of the rolled bar was posited at 30.6 mm, and the major and minor axes of the oval groove were 40.6 and 21.3 mm, respectively. The roll radius was set at 155.5 mm. The rolling speeds were assumed to be 1, 2, 3, 7, 10, 15, and 20 m/s. The following relation (Ref 8) was used to calculate the strain rates at the different rolling speeds:

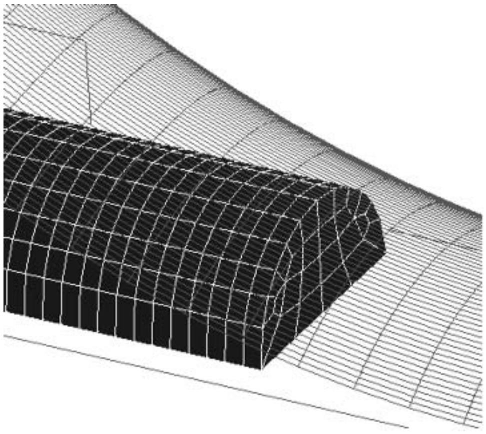

Fig. 2 Geometric model used in numerical simulation

$$\dot{\varepsilon} = 2\pi N \frac{A_0 - A_1}{A_0}\sqrt{R(H_0 - H_1)} \qquad \text{(Eq 12)}$$

The friction coefficient was assumed to change as a function of rolling speed, analogous to the relation proposed by Bachtinov (Ref 1):

$$f = 0.55K_1(1.05 - 0.0005T) \qquad \text{(Eq 13)}$$

where K_1 depends on the rolling speed used (Table 4) (Ref 1).

In Fig. 3, the vertical force acting on the roll is plotted as a function of the simulation step for two values of rolling speed (i.e., 1 and 2 m/s). As can be seen after an initial transient, the vertical force reaches a nearly constant value.

Figure 4 shows the trend of the mean vertical force as a function of the rolling speed. The specific contact pressure is calculated by dividing the mean vertical force acting on the roll by the contact surface value.

Figure 5 illustrates the contact area assumed for the numerical simulation. To estimate its value, the surfaces were measured by means of suitable software. The relevant value was estimated to be 1185 mm^2 with a measurement error less than 10%.

In Fig. 6, 7, and 8, the specific contact pressures are shown as a function of the rolling speed. These values were calculated based on both the Ekelund model (Eq 1) and the industrial approach (Eq 4). To determine the contact area, the procedures proposed by Wusatowski (W), Shinokura-Takai (S-T), and Lee-Choi-Kim (L-C-K) have been used. The value obtained by the numerical simulation has been reported.

More specifically, Wusatowski suggests calculating the contact area as the product of the contact arc length (L) and the mean value of W_0 and W_1. According to Shinokura-Takai, the contact area is half the area of the ellipse having a major semiaxis length of contact arc ($L_{\max}$) and minor semiaxis C_x (Ref 9).

$$A_{\text{S-T}} = \frac{\pi}{2} L_{\max} C_x \qquad \text{(Eq 14)}$$

Finally, Lee, Choi, and Kim posit that the contact area should equal to 3/2 of the product of ($L_{\max} \times C_x$) (Ref 9).

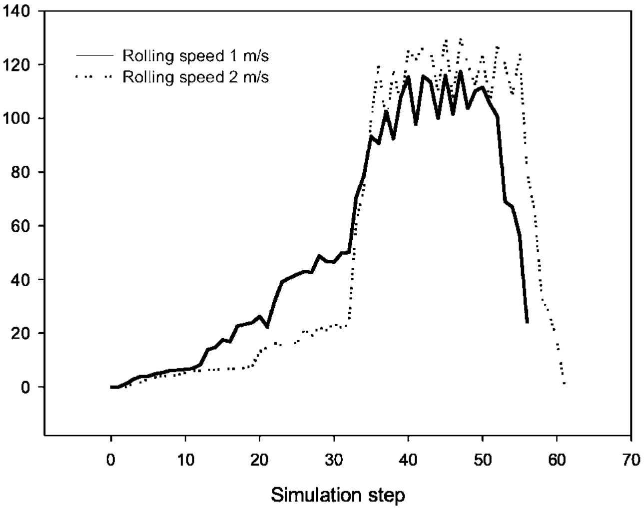

Fig. 3 Variation of the vertical force for two rolling speeds during a round-oval pass

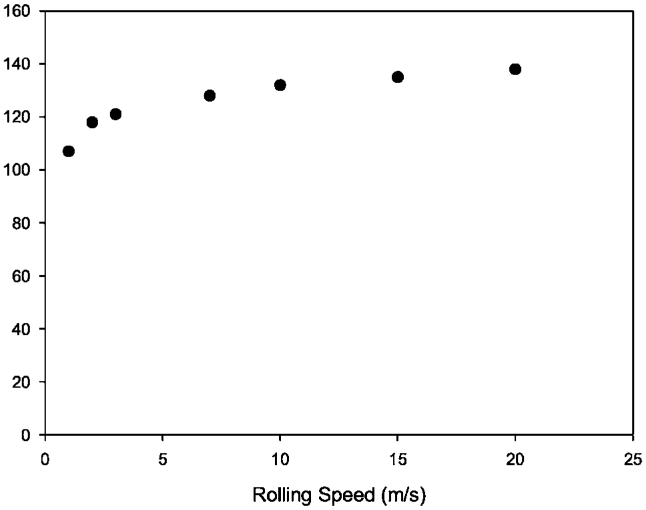

Fig. 4 Variation of the mean vertical force versus the rolling speed in a round-oval pass

Table 4 Coefficient K_1 for the friction coefficient

v, m/s	**K_1**
Up to 2	1
3	0.9
7	0.6
10	0.52
15	0.44
20	0.41

$$A_{\text{L-C-K}} = \frac{3}{2} L_{\max} C_{x} \tag{Eq 15}$$

Table 5 reports the numerical values of H_0, H_1, W_0, W_1, C_x, contact arc (L), and contact area (A).

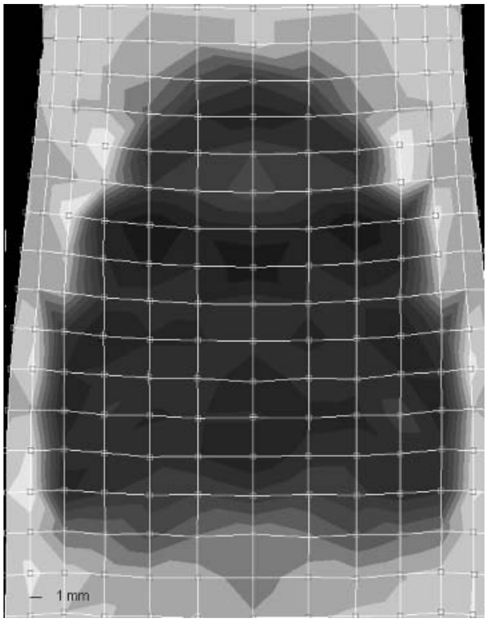

Fig. 5 Contact area measured during an FEM simulation

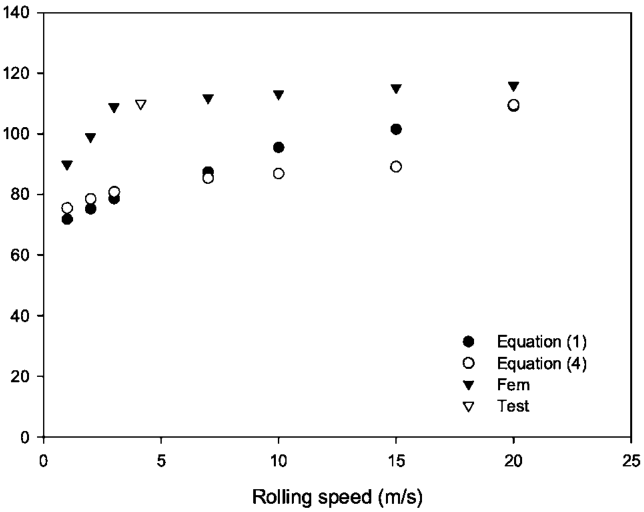

Fig. 6 Specific contact pressure versus rolling speed. Contact area calculated according to Wusatowski

Figures 6, 7, and 8 also show the value associated with a rolling speed of 4.14 m/s. This value was obtained in an industrial steel rebar manufacturing plant by measuring the absorbed power level and determining the force exerted on the rolls based on this value. The contact area was estimated by the method proposed by Wusatowski, i.e., as the product of the contact arc length (L) and W_{med}. The latter was calculated as the mean value of the incoming workpiece (bar diameter) and the width of the outgoing one (assumed equal to $W_{\max}$). The length of the contact arc L was calculated with reference to the values of H_0 and H_1. H_0 is equal to the ratio of the area to the width of the incoming workpiece, and H_1 is equal to the groove area to the width of the outgoing workpiece ($W_{\max}$).

4. Conclusions

Contact pressure values determined by the methods of Ekelund (Ref 1) and Cook-McCrum (Ref 2) (the latter being

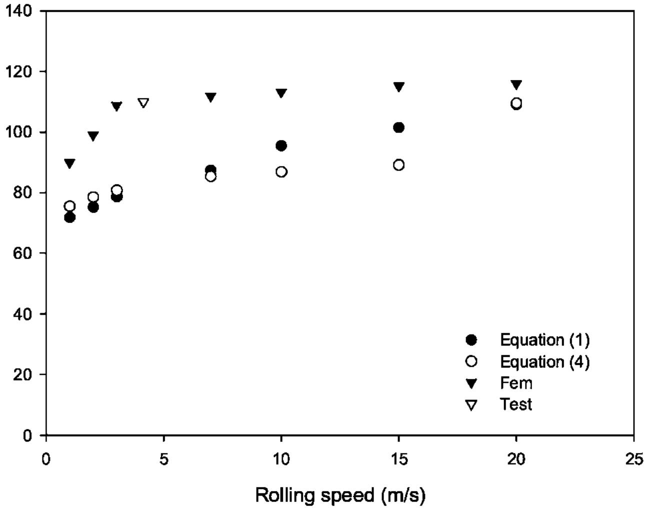

Fig. 7 Specific contact pressure versus rolling speed; contact area calculated according to Shinokura-Takai

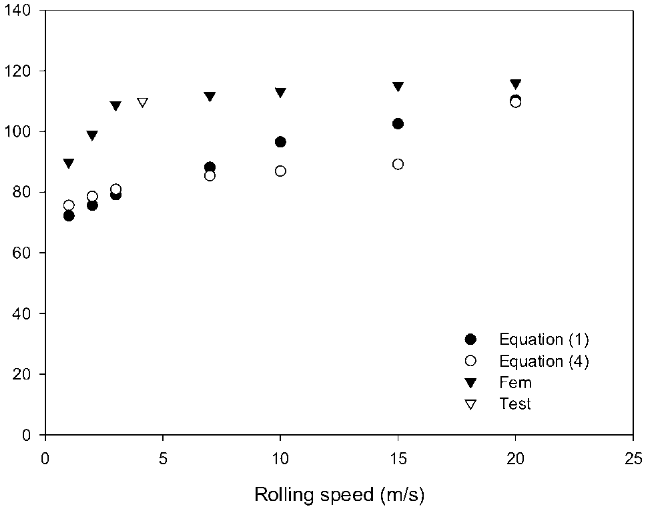

Fig. 8 Specific contact pressure versus rolling speed; contact area calculated according to Lee, Choi, and Kim (Ref 5)

Table 5 Geometrical values of the rolled bar for the round-oval pass

Analytical model	H_0, mm	H_1, mm	W_0, mm	W_1, mm	C_x, mm	L, mm	A, mm
W	24.00	20.00	30.6	40.60	15.90	24.9	887.8
S-T	22.81	13.51	30.6	37.57	15.90	38.0	951.1
L-C-K	24.00	17.24	30.6	37.57	15.90	38.0	908.7

W, Wusatowski (Ref 1); S-T, Skinokura-Takai (Ref 4); L-C-K, Lee-Choi-Kim (Ref 5)

widely used in industry) approximate those obtainable with the FEM technique.

These results were validated by comparing them with test values measured in an industrial plant. The differences between the empirical and FEM values were found to be smaller at high rolling speeds.

The most accurate specific contact pressure values are those obtained with the Ekelund formula in combination with Shinokura-Takai's contact area computation method.

The greater differences in pressure observed at low speeds are probably due to the fairly low value of K_c. Hence, the need to define a new formula and use it in place of Ekelund's approach when calculating K_c was developed.

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