ANALYTIKOEXPERIMENTAL INVESTIGATION OF
METAL POWDER DEFORMATION IN ROLLING

Yu. I. Kovalenko and G. A. Vinogradov

The metal powder rolling process is influenced by a variety of factors, among which there are some
complex relations with different degrees of indeterminism. In this connection, the present work was under-
taken with the aim of conducting an analytikoexperimental investigation of metal powder deformation with
the aid of methods of industrial cybernetics [2].

A sufficiently full mathematical description of the dynamics and statics of metal powder rolling, en-
abling the controlling parameters to be adjusted in the course of the process to correct any changes in the
parameters of the stock being rolled, can be obtained by examining simultaneously the material and energy
balances, the physical and technological properties of the powder charge, the effect of the ambient atmos-
phere on the course of the process, and the parameters of the metal powder rolling mill.

The parameters of metal powder strip (thickness, density, etc.) evolve during the rolling process
through the interaction of all the geometric and physicomechanical parameters of the system (composed of
the mill drive, mill, powder charge, and ambient atmosphere), which are connected with one another by
complex relationships [1]. The metal powder rolling process is characterized by a long steady-state period.
A sufficiently full mathematical description of the static conditions of metal powder rolling can be obtained
by examining simultaneously the material balance of rolling and the geometric parameters of the deforma-
tion zone. For this purpose, use can be made of the following well-known material balance equation:

\[ z = \frac{1}{\beta r} \left( 1 + \alpha^2 \frac{R}{h} \right) \]  

(1)

where \( z \) is the densification coefficient, \( \beta = b_s/b_p \) is the width coefficient, \( \tau = f \left( \nu \right) \) is a coefficient depend-
ing on the rolling speed, \( \nu \) is the rolling speed, \( R \) is the roll radius, \( h \) is the strip thickness, and \( \alpha \) is the
rolling angle.

An analytical expression for the densification coefficient in powder rolling and its geometric rep-
resentation can be established with the aid of regression analysis, in the form of the following functional
relation:

\[ z = f \left( \beta, \frac{1}{\nu}, \frac{R}{h} \right) \]  

(2)

The formula (2) and its geometric representation will reflect the statics of the rolling process and,
ence, the interrelationship between deformation coefficients in rolling. Finding an analytical expression
for these coefficients presents considerable difficulties, which have not yet been overcome.

An experimental investigation of the densification coefficient was carried out using a rolling mill
with two driven rolls. The rolls, 202 mm in diameter, were made of alloy steel, and had a surface hard-
ness of 48-50 Rockwell C and a Class 6 finish. Powder was fed to the rolls in a vertical direction under
gravity or by means of a suspended hopper device of 120-mm width. Strip rolling was performed at speeds
ranging from 0.074 to 0.323 m/sec. The strip parameters (thickness, width, and density) were varied by
altering the angle of contact between the powder and the rolls and the gap between the rolls.

Institute of Materials Science, Academy of Sciences of the Ukrainian SSR. Translated from Porosh-
The Kh18N15 stainless steel powder chosen for investigation had the following particle size distribution:

<table>
<thead>
<tr>
<th>Particle size, mm</th>
<th>Amount, wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.065</td>
<td>3.3</td>
</tr>
<tr>
<td>+0.065</td>
<td>12.7</td>
</tr>
<tr>
<td>+0.080</td>
<td>10.2</td>
</tr>
<tr>
<td>+0.090</td>
<td>13.7</td>
</tr>
<tr>
<td>+0.100</td>
<td>16.3</td>
</tr>
<tr>
<td>+0.125</td>
<td>15.2</td>
</tr>
<tr>
<td>+0.160</td>
<td>28.5</td>
</tr>
<tr>
<td>+0.250</td>
<td>20.7</td>
</tr>
<tr>
<td>+0.400</td>
<td>10.2</td>
</tr>
</tbody>
</table>

The powder had a mean weighted particle size of 0.108 mm, a specific surface of 20 m²/g, and a tap density of 2.68 g/cm³.

The number of experiments was chosen so as to satisfy the relation [5]

\[ N \geq C_k + d \]  \tag{3}

where \( k \) is the number of independent variables and \( d \) is the degree of the polynomial. The results of determinations of the densification coefficient are represented by a polynomial of the second degree, the number of independent variables being \( k = 2 \). Hence, the necessary number of experiments is \( N \geq C_2^2 + 2 = 6 \). It was therefore decided to perform 10 rolling operations. After the experiments, the results of which are presented in Table 1, the starting data were checked for uniformity [9].

The maximum and minimum significance limits of strip thickness were determined from the expression

\[ h = \bar{h} \pm U_{0.99} \sigma, \]  \tag{4}

where \( \bar{h} \) is the arithmetic mean value of \( h \), \( U_{0.99} = 2.326 \) is the quantile of normal distribution, and \( \sigma \) is the root-mean-square deviation. The experimental data obtained made it possible to assert with a probability of 0.99 that, for constructing a mathematical model of the rolling of Kh18N15 stainless steel powder, use should be made of the results of experiments Nos. 2, 4, 5, 6, 8, and 10.

In practice, when obtaining a mathematical description of a process, it is most convenient to use a portion of a Taylor's series as an analytical representation of an unknown function [5]. In the solution of a problem of this type, it is only necessary to employ the following incomplete quadratic equation:

\[ y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i<j}^{k} b_{ij} x_i x_j, \]  \tag{5}

where \( b_0, b_1, \) and \( b_{ij} \) are randomly evaluated regression coefficients. In the present work, these were determined by the least squares method, using pair correlation coefficients [4]. The system of normal equations was solved by the method of successive exclusion of unknown coefficients.

Calculated values of regression coefficients were substituted into Eq. (5), which yielded a full-scale mathematical model of the densification coefficient allowing for powder losses due to spillage:

\[ z = \beta \left( -0.418 + 0.045 \frac{1}{v} + 0.033 \frac{R}{h} - 0.728 \cdot 10^{-5} \frac{R}{v h} \right). \]  \tag{6}

The adequacy of the model obtained was assessed with the aid of the factors \( \varepsilon \) and \( F \), which were equal to 0.011 and 51.2, respectively. A check of the significance of the multiple regression coefficients and the multiple correlation ratio \( \eta^2 \) with the factor \( t \) for the 5% level of significance demonstrated that they were all significant: \( t_\eta = 345.0, t_\varepsilon = 48.1, t_1 = 19.2, t_2 = 136.0, \) and \( t_{12} = 20.5 \). The tabular values of the factors \( F \) and \( t \) were 45.4 and 2.58, respectively. The coefficient of multiple determination, \( \eta^2 \), showing the extent of the influence of specific factors chosen from among all those affecting the densification coefficient, was found to be equal to 0.99. To evaluate the reliability of the model obtained, confidence limits were established for each

*An 18% Cr-15% Ni grade — Translator.