Investigation of energy-power parameters of thin sheets rolling to improve energy efficiency

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Abstract. In order to study processes occurring during manufacturing of thin steel sheet by cold rolling and change of energy-power parameters, simulation was performed using engineering software DEFORM 3D, which allows to reflect rolling technology accurately. Model of treatment process was created, output data, modes and temperature of treatment, motion parameters of rolls and sheets were set, material of workpiece was selected and its properties were determined. During simulation of sheets cold rolling process, Lagrange analysis was used, number of simulation steps was 100. Process of plastic deformation of metal along curved grid was investigated, vector displacement field was determined, and it was found that maximum movement of metal occurs under effect of top roll. Distribution of stress-strain state was investigated and maximum stress in strain zone was determined. Distribution of rolling forces and torque was investigated, which allowed to determine their maximum values. Maximum rolling forces and torque were observed at 7 – 9th second of treatment, and in future they were reduced due to the fact that pushing force disappeared and steady process began.

1. Introduction
Cold rolling technologies are widely used for thin sheets manufacturing, which allows to obtain products of exact size and high quality. Process of metal treatment by pressure is quite labor intensive and energy consuming. Cold rolling leads to significant changes in the metal structure. Distribution of strains and stress during reduction during cold rolling is difficult to investigate in production conditions, because of very high cost of such experiments.

Currently direction, connected with computer designing of metal treatment by pressure processes has been formed in science at sufficiently high level. Computer programs allow to create models that accurately reflect treatment parameters, where you can track all transformations that occur during reduction.

Investigation of cold rolling with help of DEFORM 3D engineering software is relevant, because it allows to significantly reduce time for conducting experiments, accelerate determination of rational modes of reduction during thin sheet cold rolling, which reduce energy consumption costs, improve product quality, increase efficiency and decrease self-cost of process.

Task to improve rolling technology using rational reduction modes, which provide required quality of products with minimum energy consumption is relevant.
For this purpose, it is necessary to carry out research of metal treatment using DEFORM 3D computer software, which significantly speeds up treatment process improvement.

Purpose of this work is to study cold rolling of thin sheets using DEFORM computer software to determine rational energy-power parameters.

2. Analysis of literature data and problem definition

Within framework of stable metallurgy development program, team of scientists from Ferrous metals metallurgy and foundry Department of Kryvyi Rih National University deals with following important tasks: improvement of sheet rolling technology and improving quality of manufactured products [1]. Another area of research is development of recommendations for improving energy efficiency of cold rolling technologies.

Thin sheets manufactured by rolling are widely used in vehicle manufacturing industry and engineering industry. Thin steel sheets are mainly produced on cold rolling mills. This process allows to obtain sheet thickness of $0.15 - 1.8 \text{mm}$ and width of $700 - 2300 \text{mm}$, tin plate and stripes with thickness of $0.0015 \text{mm}$. Starting material for cold rolling is steel having thickness of $1.6 - 6 \text{mm}$ [2]. This steel is obtained by hot rolling in a rolling mill in hot rolling shops.

Production of cold-rolled sheets manufactured in cold rolling workshops involves large number of stages and requires usage of various and sophisticated equipment [3].

Cold-rolled sheets are produced on continuous or semi-continuous rolling mills. They have a large number of work stands, which shall be adjusted. Cold-rolled sheet steel shall have high strength. Its surface shall be matt in some cases and polished in other cases.

Cold rolling significantly changes metals properties: as value of reduction increases, yield strength of metal and deformation resistance increase, elongation of strip decreases. This is due to the change of grains size during cold deformation, which leads to change of metal structure.

There is non-uniform distribution of friction forces [4], which affects deformation process. All these factors affect change of energy consumption during rolling, which affects cost of rolling production. Cold rolling processes require further investigation, research and refinement to improve product quality, reduce power costs and cost of production.

Volumetric displacements occurring in strain zone during rolling are not available for direct study, and experiments cannot cover the whole set of interaction of reduction technological factors, that’s why many results have individual characteristics and can only be used for conditions in which they were obtained [5].

It is known that during rolling a strain zone is formed, which consumes a lot of energy and creates complex stress-strain state of metal [6–8].

Studies [9, 10] use large number of numerical one-dimensional models, which enable to take into account nature of geometric parameters distribution, mechanical properties and conditions of contact friction in strain zone of rolling process of thin sheets and steel strips.

Mathematical models [11,12] show cold rolling processes and power calculations, but do not take into account dynamic nature of process.

Dynamic models [13–15] do not account for foreseen stresses and strains during cold rolling. The work [16] does not take into consideration contact interaction between material and rolls. Computer simulation methods offer great opportunities for solving problems of metal treatment by pressure [17]. Finite element methods, finite difference methods, boundary element method and finite volume method [18] have become very popular in theory of metal treatment by pressure.

A large number of studies using finite element methods [19,20] were devoted to problem of metal flow during deformation. But it shall be noted that in these works process of thin sheets cold rolling was not investigated. In article [21] engineering software complex DEFORM 3D was used to study processes of sheets hot rolling, where nature of metal form changing, forming of
products microstructure, energy costs for process were carefully studied, but characteristics of cold rolling of thin sheets were not investigated.

Therefore, authors consider it necessary to pay attention to energy consumption during cold rolling of thin sheets using DEFORM 3D software.

3. Purpose and tasks of research
Purpose of work: to investigate cold rolling process of thin steel sheet using DEFORM 3D software to determine energy-power parameters of process. In order to reach this goal, following tasks were set:

- to create model of cold rolling of thin sheet in DEFORM 3D software;
- determine forces and torques that arise during deformation process and their distribution in strain zone during cold processing.

4. Research Methodology
Sheet with length of $l = 1000\, mm$, width of $b = 1000\, mm$ and height of $h = 5\, mm$ was used to simulate cold rolling. Rolling was carried out in cylindrical rolls. Roll diameter is $200\, mm$, length is $1200\, mm$. Initial temperature of rolling process was $20\, ^\circ C$. Research is aimed to investigate change of stress in strain zone, which occurs during rolling (figure 1). Change of stress value leads to change of force and energy consumption.

![Figure 1. Deformation scheme: $ABB'A'$ is strain zone; $h_0$ is sheet thickness before rolling; $h_1$ is sheet thickness after rolling; $b_0$ is strip width before rolling; $b_1$ is strip width after rolling; $\alpha$ is capture angle during rolling; $R$ is roll radius; $F_k$ is contact area of the sheet with the rolls; $l_d$ is length of the strain zone; $M$ is metal flow before entering the strain zone; $N$ is metal flow when leaving the strain zone.](image)

Uneven stresses that occur in the metal cause uneven deformations that affect surface quality of sheet. Deformation degree during study varied from 10 to 80%. Deformation degree was determined by the formula (2):
\[ \varepsilon = \Delta h / h_0, \]  
\[ \Delta h = h_0 - h_1, \]  
where \( \Delta h \) is absolute reduction, \( h_0, h_1 \) – initial and final thickness of strip accordingly.

Software DEFORM 3D simulated original workpiece, placed it in space, determined parameters of interaction between roll and workpiece, friction conditions and nature of heat exchange, positioned rolls relative to workpiece, as shown in figure 2. Diagram shows metal clamping process by rolls, which occurs at initial stage of rolling (first step of simulation).

The diagram (figure 2) shows how the interaction of the rolls and the processed material occurs (top view). Rolls reduce rolled material, rotate, strip moves gradually towards rolls rotation direction. Grid of finite elements on workpiece, number of which is 2051, was constructed. It was adjusted that main roll is top one, that reduces metal along height. Material of treated workpiece was determined from computer software library. Carbon steel sheet AISI-1015 (20-1200C) was used in research. Figure 3 presents diagram “Stress-Strain”, which shows value of stress at which plastic deformation of material begins. Yield strength of material was determined according to the energy law [17]:

\[ \sigma = \varepsilon^n u^m + y, \]  
where \( \sigma \) is effective stress of plastic material flow, \( \varepsilon \) is material deformation, \( u \) is material deformation speed; \( n \) is deformation degree indicator, \( m \) is indicator of deformation degree speed, and \( y \) is material constant.

Selected elastic properties of material are characterized by Young’s modulus and Poisson’s ratio. These coefficients are constant and are 0.3 and 1.5 \( \times 10^5 \) respectively. Heat capacity of investigated material, which depends on treatment temperature, was determined (figure 4).
Figure 3. Diagram “Stress-Strain”.

Figure 4. Dependence of heat capacity of steel on temperature.
Graph shows that heat capacity of treated steel increases with increasing of temperature and takes maximum values at treatment temperature of 210°C. This increase occurs under influence of plastic deformation. After this temperature heat capacity decreases. During simulation Perzyna’s model was used [17]:

\[ e' = \gamma (\varepsilon' / \sigma - 1) * m, \tag{4} \]

where \( \gamma \) is fluidity; \( \varepsilon' \) is effective stress; \( \sigma \) is flow stress; \( m \) is material parameter; \( e' \) is effective strain speed.

To study cold rolling process, one object was carefully positioned relative to others. Positioning accuracy was selected. Coefficient of friction during cold rolling was assumed to be 0.1. It was assumed that force of friction varies according to law of Siebel. Contact between workpiece and top and bottom rolls was generated. For simulation, it was assumed that workpiece is plastic type of object, for which analysis was performed based on specified values of metal yield strength, and roll is rigid, which means that it is not deformable object. Parameters of rolls (speed of rotation) and workpiece (linear speed of strip displacement) were specified. During simulation of sheets cold rolling process, Lagrange analysis was used, number of simulation steps was 100. Calculations were performed using the SI unit system. Simulation mode was deformation. Number of steps was determined by the formulas [17]:

\[ n = \frac{x}{(v \Delta t)}, \tag{5} \]

where \( n \) is number of steps, \( x \) is summary movement of main roll, \( v \) - main roll speed, \( \Delta t \) is time increment for one step. Theoretical study of rolling force was carried out according to the formula (2):

\[ P = \sigma n_{\sigma} b \sqrt{\Delta h R}, \tag{6} \]

where \( n_{\sigma} \) is stress coefficient (2), \( b \) is sheet width. Selected parameters of database allowed us to simulate cold rolling process, to determine its main characteristics, changes in forces and torques of deformation during treatment and to study transformation in strain zone formed during rolling.

5. Discussion of energypower parameters investigation results and identification of rational reduction modes

As result of simulation, process of metal flow along curved coordinate grid was investigated and vector displacement field was determined, which is shown in figure 5. Figure 5 shows that maximum displacement vector appears under press of upper roll at beginning of treatment. Bottom roll has less intense impact on metal because top roll is the main tool. Strain distribution in volume of treated material during cold rolling is shown in figure 6.

Stress-strain state of metal at point of its clamping by rolls was identified; maximum strain values in strain zone reach 0.309mm per 1mm of workpiece height. Change in rolling force during cold rolling in strain zone with time was investigated (figure 7), and results show that rolling force increases during the first 9 seconds and reaches 5.5 MN.

In real conditions, for these modes, the rolling force reaches 5.3 MN [8], which corresponds to a high simulation accuracy, where the error is 5.5%. Formula (6) was used to check adequacy of model. A further sharp decrease in the rolling force is explained by the fact that the process of clamping the billet with the rolls is over and a stable rolling motion has begun, when the pushing forces are removed and the metal moves without significant efforts. As result of simulation, graph of torque change over time, formed by top roll, was obtained (figure 8). Graph (figure 8) shows that torque from beginning of cold rolling of sheet steel changes periodically, reaching maximum values at 7th second from process beginning. Studies show that power consumption
Figure 5. Vector displacement field of metal during rolling.

Figure 6. Strain distribution during cold rolling.
at beginning of cold rolling process increases rapidly and reaches maximum values at $7 - 9^{th}$ second under effect of upper roll and subsequently decreases. Checking of investigation results regarding torque during cold rolling was carried out according to the formula:

$$M = P\psi \sqrt{R\Delta h},$$

where $\psi$ is moment arm ratio.

Rolling force was applied to the center of strain zone. Torque arm was calculated by the following formula:

$$\psi = \frac{1}{2}R\sin\alpha,$$

Capture angle was calculated by the formula:

$$\alpha = \sqrt{\frac{\Delta h}{R}},$$

Parameters obtained during simulation were used for further theoretical calculations of work applied for rolling process and process capacity. Rolling work was determined taking into account symmetrical rolling process according to the formula:

$$A = \frac{2Ml_d}{R(1 + S)},$$

$$S = \frac{R}{h_1}\gamma^2,$$

where $\gamma$ is angle of neutral plane, where speed of rolls is equal to speed of metal. Angle of neutral plane depends on capture angle and friction coefficient. It is calculated by the formula:

$$\gamma = \frac{\alpha}{2}(1 - \frac{\alpha}{2\beta}),$$

where $\beta$ is friction angle. Cold rolling enables treatment in case if friction angle is $\beta = 0.1$. Capacity that was used on cylindrical part of roll was determined by the formula:

**Figure 7.** Change of rolling load over time.
Figure 8. Torque change.

\[ W = \frac{2MI_d}{R(1 + s)\tau}, \]  

(13)

where \( \tau \) is time of rolling.

Research enabled to choose rational treatment modes for cold rolling: efficient degree of deformation \( \varepsilon \) of 70% is accepted. This degree of deformation enables to obtain sheets with maximum hardness, and they can deform plastically. Increase of deformation degree requires increase of energy consumption. Increasing of deformation degree leads to elastic displacement of rolls, which makes quality of sheet surface worse. With increase of deformation degree, stress of metal surface layer increases, as well as rolling force and torque, and process defects may appear: microcracks, microfiber on sheets and rolling tools. Reduction of deformation degree up to 45% leads to decrease of strength and hardness of metal. Sheet is able to deform plastically under load during operation. Investigation results are shown in table 1. Executed research enabled to use efficient modes of reduction (table 1) when developing new technological process for manufacturing thin sheets by cold rolling, which ensures sustainable development of cold rolling technologies.

| \( \sigma, MPa \) | \( b, mm \) | \( h_0, mm \) | \( h_1, mm \) | \( \varepsilon, \% \) | \( P, MN \) | \( M, MNm \) |
|---|---|---|---|---|---|---|
| 740 | 1000 | 5 | 1,5 | 70 | 5,3 | 0,198 |

Such modes will make it possible to obtain cold-rolled sheets with high strength characteristics at a minimum cost.

6. Conclusions
As result of investigation of cold rolling of thin steel sheets was executed following:
model of cold rolling of thin sheets in DEFORM 3D software was created and research methodology was developed, which allowed to determine changes of energy-power parameters that occur in strain zone during treatment; vector field of metal movement and its stress-strain state during cold rolling of thin sheets were determined;

there were determined forces and torques that arise during deformation process, and there was investigated their distribution in strain zone during cold treatment, which made it possible to determine rational energy consumption during cold rolling;

simulation showed that stress reaches its maximum during 9th second of treatment $5.5\, \text{MN}$ during cold rolling, and accuracy of simulation is $5.5\%$.

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