A Hybrid Method to Deformation Force of High-speed Cold Roll-beating Forming

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ABSTRCT: *High-speed cold roll-beating forming technique is a new near-net plastic forming method that the intermittent high-speed roll-beating is used to achieve dynamic impact local loading, and that is fast, transient, high impact, large deformation of the complex forming process. For this forming process, the main stress method is employed to derive an analytic formula for the deformation force. Taking into account the main stress method can not reflect impact factors such as high-speed transient roll beating in process of this analytic solution, then the ABAQUS/Explicit is applied to simulate for high-speed cold roll- beating. The regression analysis is used to correct for the analytic formula based on simulation results, which makes the analytic formula more accurate reflection of deformation force of the different technological parameters of high-speed cold roll-beating. The forming experiments are carried out with self developed high-speed cold roll-beating experimental equipment and the experimental of deformation force is measured to verify the correctness of the corrected analytic formula.*

Categories and Subject Descriptors:
H.4.3: [Communication hardware]: Electro-mechanical devices

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1. Introduction

With the increasingly drastic marketing competition and fast updating of products, many drawbacks such as long time production preparation, equipment of large tonnage, poor processing flexibility and high manufacturing costs by the traditional die forming process are reflected day by day [1]-[2]. In order to adapt to the market demand of the rapid product updating in modern manufacturing field, many scholars committed to the new dieless (or flexible die) precise plastic forming process combining with high speed and efficient [3]-[5]. Cold roll-beating forming technique is a near-net shaping technology, in which the rotating rigor roller with the specific tooth profile rolls and beats the blank with high speed, owing to the plasticity of metal itself, the surface metal of the blank plastically flows, and forming of work-piece overall by cumulating deformation of continuous tiny region with the relationship of relative motion between the rigor wheel and blank is realized. So it is a forming technology with no-die, no constrains and free shaping. Krafenbauer H. and Ernst Grob initiated the cold roll-beating shaping for tooth profile and presented the method that the rotating roller stoke the blank to shape the spline tooth on a NC machine, which is usually called Grob method.

Deforming force of cold roll-beating directly affects metal flow of forming process, thereby affecting geometry of the forming surface, and will influence part quality finally. It plays an important role in the research of cold roll-beating forming as a key factor affecting forming mechanism and precision [5]-[6]. At the same time, deforming force is also an important basis for equipment design, tool strength verification and reasonable technology parameters determination. So, in scientific study and engineering practice, an approximate deforming force computation method that is simple but meanwhile is of certain precision is needed. The basic theoretical methods such as Slab Method, UBET, Slip Line Method, FEM, and FVM have been used in the research of metal plastic forming technology [7]-[8]. In [9], force of tube extrusion about cone dies was studied theoretically and the both formulas were determined respectively by means of slab method and the method of balance of work.. In [10], an analytical model for predicting the rolling force and rolling torque during snake rolling was constructed by using slab method, and, the accuracy of the analytical model was verified by the comparison between the analytical and experimental results. Theses forming technologies can be considered as local static loading problems, while the cold roll-beating forming belongs to dynamic impact loading, thus it will be difficult to solve the deforming force only slab method is used. In [11], the sheet forming simulation of rectangular box was conducted and the method of determining VBHF (variable blank holder force) were proposed based on the displacement in the Z direction of blank holder. In [12], based on the method of numerical simulation, the diameter of steel billet, entrance half angle of concave die and the dimension of spline were analyzed for the forming force on the spline processing with the help of a rigid-plasticity finite element software Deform-3D. Both of them used FEM to obtain the deforming force, and only some confirmatory results can be obtained. So, if only FEM is used, it is difficult to obtain a complete theoretical empirical formula.

As a new forming method under dynamic local loading, high-speed cold roll-beating adopts intermittent reciprocate beating to realize dynamic impacting loading, the deforming mechanism is very complex, and the research object is of solid functional surface, which results in greater uncertainty in metal flowing, so merely using analytic method such as slab method to resolve the deforming force can only be an approximate resolving method, which cannot take into account the effect of the strain on the deforming force, i.e. effect of the high-speed reciprocating beating cannot be completely taken into account. Meanwhile, though merely using simulation method to obtain the deforming force can study the effect of technology parameters on the force, the simulating process is very time-consuming, if the forming conditions are changed, simulation model re-building is needed.

In this paper, a new method combining slab method and simulation method to resolve high-speed cold roll-beating deforming force is presented. Firstly, slab method is used to obtain the analytic resolution of the deforming force, then ABAQUS/Explicit is used to simulate the forming process and the simulating results are used to modify the analytical values, thus the deforming forces of high-speed cold roll-beating under different process parameters can be more precisely determined with the modified analytical results.

2. Principle of Cold Roll-beating

High speed precision cold roll-beating is typical of precise plastic forming technology. In the forming process, by taking advantage of the inherent plasticity of rough material at ordinary temperatures, the roller with certain shape and high speed rotation, roll-presses and beats the rough blank intermittently, forcing the local metal of the rough surface flow, plastic deformations of continuous accumulate to form the profile of the required part [7].

The working principle of slab cold roll-beating is shown in the Figure 1. The rollers of certain shape are mounted on a rotating shaft with high speed evenly. In the cold roll-beating forming, slab blank feeds horizontally; the rollers with high speed rotation beat the slab blank intermittently; metal materials of slab blank surface move a certain displacement due to high speed impact of the rollers. The roller rotates around its own axis the moment the roller contacts with the slab because of the action of the friction between them, thereby the rolling between the roller and the slab is ensured. The action is repeated until the specific shape is formed eventually in the slab blank to satisfy the predetermined depth of cut (rolling reduction).

According to the direction of metal flow, the deforming force of cold roll-beating is divided into CFN_X, CFN_Y and CFN_Z. The paper focuses on the changes of radial deforming force (CFN_X), and the effects of process parameters (rolling reduction, feed rate and different speed) on the deforming force.

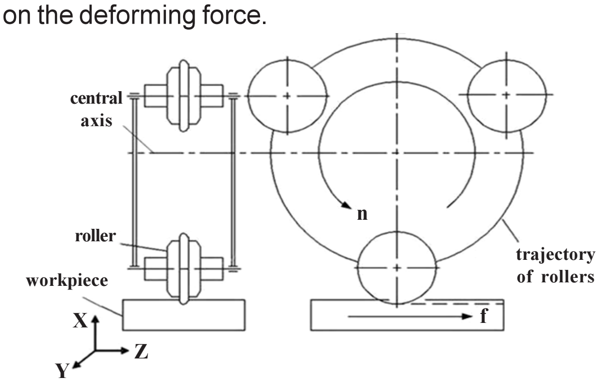


Figure 1. Principle of slab cold roll-beating forming

3. Analysis of Cold Roll-beating Deforming Force

Slab method is a commonly used approximate resolving method for calculating the deforming force in plastic processing. While using the method, firstly the corresponding physical model is built to obtain the geometry and mechanics relation between the roller and work-piece, then simplifying assumptions of stress status are made and the simplified equilibrium differential equation expressed by the principle stress and mathematical model of high-speed roll-beating under plastic condition are built, finally the calculation formula for deforming force can be obtained which can intuitively reflect the effects of process parameters on the deforming forces.

3.1 Physical Model

While solving the deforming force, certain simplifications are made, it is assumed that the work-piece is fixed without moving and roll-beating of the roller on the work only occurs once. The corresponding physical model is shown in the Figure 2, R_s is the radius of the roller, R_ρ is the fillet radius of the roller, R_D is the turning radius of the roller, f is the rolling reduction, a is the radial distance between axis center and the work-piece blank edge in xoy plane, ρ and $d\rho$ are the offset angle and its increment individually in xoz projection plane, θ and $d\theta$ are the radius and its increment of the micro-unit corresponding to the center of the roller fillet individually, A_1, A_1', A_2 and A_2' are individually lateral areas of EFGH, ABCD, BFCG and ADEH, σ_1, σ_2, σ_3 are individually radial, tangential and axial stresses of the micro-unit.

stress state, the deforming is mainly radial compressing and axial tensile, thus the tangential deforming is neglected and the deforming process can be considered as plane stress state.

(2) The contacting shape between the roller and work blank is considered as ideal and the material is homogeneous and isotropic, while instantaneous deforming occurs in the contacting zone with the roller, no deforming occurs in other zones.

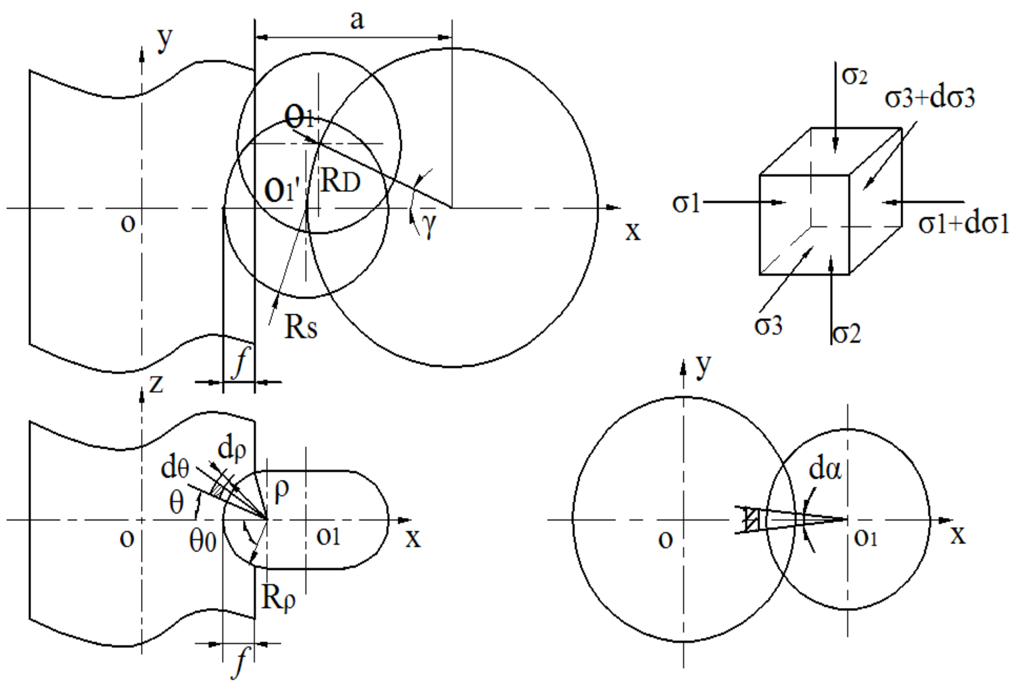


Figure 2. Mechanical deformation zones and geometry relationship

During the procedure of roller roll-beating the work-piece blank, if defining γ as angle between center of roll-beating axis and x-axis in xoy plane, the rolling reduction f will change with γ. The relation between θ_0 and f can be written as $\theta_0 = \arccos\left(\frac{R_\rho - f}{R_\rho}\right)$ and $f = R_s - (a - R_D \cos\gamma)$.

While $\gamma = \gamma_0$, f is of its minimum value, i.e. the roller just contacts with the work, $\theta_0 = \theta_{0\,min}$. While $\gamma = 0$, f is of its maximum value, $\theta_0 = \theta_{0\,max}$. According to the geometry relation, $\gamma_0 = \arccos\left(\frac{a - R_s}{R_D}\right)$ can be deduced.

Meanwhile, the stress status of a unit in the deforming zone are following. (1) The stress status of the unit in contacting zone of the blank with the roller is compressive stress. (2) The unit is of three dimensional stress state. (3) Friction force exists while the roller contacts the blank.

3.2 Mathematical Model

Based on the physical model above, assumptions are made while solving the deforming forces as following.

(1) The unit in the deforming zone is of three dimensional

(3) The frication force between the roller and blank is neglected.

(4) The volume of work-piece remains unchanged before and after deforming.

(5) During deforming process, the equipment and tool are considered as rigid, the centrifugal force and force of gravity are not taken into account.

(6) Effect of roll-beating velocity on the deforming force is neglected.

3.2.1 Stress of the deforming zone

While determining the stress of deforming zone, firstly unit with certain shape is cut from the deforming zone of the work, then the stress equilibrium equation is built according to the stress feature of cold roll-beating process, finally the deforming force expressions are deduced according certain boundary conditions and yield criterion.

From the Figure 2, the stress equilibrium equation of axial direction can be built as following.

$$\sigma_1 A_1' \sin(\theta + d\theta/2) - (\sigma_1 + d\sigma) A_1 \sin(\theta + d\theta/2) - \sigma_3 A_2' \cos\theta + (\sigma_3 + d\sigma_3) A_2 \cos(\theta + d\theta) = 0 \quad (1)$$

While neglecting the third order minimal items, formula (1) can be simplified as:

$$(\sigma_1 - \sigma_3)\, d\theta\, d\rho - \rho d\theta\, d\sigma_1 + \cot\theta\, d\rho\, d\sigma_3 = 0 \qquad (2)$$

As the deforming zone being in the plane strain state, and the stresses of 3 directions are of compressive stress, it is known that $\sigma_3 > \sigma_2 > \sigma_1$ according to consistent relationship between the stress and strain components, then the intermediate principal stress can be obtained as following

$$\sigma_2 = \frac{1}{2}(\sigma_1 + \sigma_3) \qquad (3)$$

According to the yield criterion,

$$\sigma_1 - \sigma_3 = \beta \sigma_s \qquad (4)$$

where σ_s is the yield limit of the material.

As the deforming zone is in the plane strain state, which means that $\varepsilon_2 = 0$. According constant volume principle in plastic deforming $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$, then $\varepsilon_1 = -\varepsilon_3$, thus

$$\bar{\varepsilon} = \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} = \frac{2}{\sqrt{3}}\varepsilon_1 \qquad (5)$$

Inserting (4) to (2) and integrating

$$\sigma_1 = (\beta\sigma + \frac{\cot\theta}{d\theta} d\sigma_3)\ \ln\rho + C_1 \qquad (6)$$

Where C_1 is a constant.

While $\rho = R_\rho + h$, $\sigma_1 = \sigma_s$, $(\beta\sigma + \frac{\cot\theta}{d\theta} d\sigma_3) \ln (R_\rho + h) + C_1 = \sigma_s$, so $C_1 = \sigma_s - (\beta\sigma + \frac{\cot\theta}{d\theta} d\sigma_3) \ln(R_\rho + h)$.

Substituting C_1 to expression (6), $\sigma_1 = \sigma_s + (\beta\sigma + \frac{\cot\theta}{d\theta} d\sigma_3) \ln \frac{\rho}{(R_\rho + h)}$. Substituting expression (4) to above expression, $\sigma_3 = \sigma_s (1 + K_1\beta - K_1\beta) + \frac{\cot\theta}{d\theta} d\sigma_3 K_1$, where $K_1 = \ln \frac{\rho}{(R_\rho + h)}$.

Integrating again, $K_1 \ln [\sigma_3 + \sigma_s(\beta - 1 - K_1\beta)] = -\ln\cos\theta + C_2$, where C_2 is a constant.

While $\theta = \theta_0$, $\sigma_3 = 0$, thus $C_2 = K_1 \ln [\sigma(\beta - 1 - K_1\beta)] + \ln \cos\theta_0$, substituting C_2 to above expression, the following can be obtained.

$$\sigma_3 = \sigma_s [\cos\theta^{\frac{1}{K_1}} \cos\theta_0^{\frac{1}{K_1}} (\beta - 1 - K_1\beta) - (\beta - 1 + K_1\beta)] \qquad (7)$$

Substituting expression (7) to (4), the following can be deduced.

$$\sigma_3 = \sigma_s [\cos\theta^{\frac{1}{K_1}} \cos\theta_0^{\frac{1}{K_1}} (\beta - 1 - K_1\beta) + K_1\beta + 1] \qquad (8)$$

While $\rho = R_\rho$, σ_1 determined from the above expression is the contacting stress σ_c between the roller and the work blank, so

$$\sigma_c = \sigma_s [\cos\theta^{\frac{1}{K}} \cos\theta_0^{\frac{1}{K}} (\beta - 1 - K\beta) + K\beta + 1] \qquad (9)$$

where, $K = \ln \frac{R_\rho}{(R_\rho + h)}$.

The contact stress at different position of the roller is different, averaging the contact stresses along the contacting limit, the average contact stress is:

$$\bar{\sigma}_c = \frac{\int_0^{\theta_0} \sigma_s [\cos\theta^{-\frac{1}{K}} \cos\theta_0^{\frac{1}{K}} (\beta - 1 - K\beta) + K\beta + 1]\, d\theta}{\theta_0}$$

i.e.

$$\bar{\sigma}_c = \frac{\sigma_s \cos\theta_0^{\frac{1}{K}} (\beta - 1 - K\beta)}{\theta_0} \int_0^{\theta_0} \cos\theta^{-\frac{1}{K}} d\theta + \sigma_s (K\beta + 1)\, d\theta \qquad (10)$$

3.2.2 Contact area between the roller and work

Radial, axial and tangential projections of the contact zone between the roller and work are made, then the radial projection area Sr, axial projection area Sz and tangential projection area St can be obtained, as shown in the Figure 3 ~ 5.

As shown in the Figure 3, the radial projection area Sr can be expressed as $Sr = \pi mn$, where $m = R_\rho \sin\theta_0$, $n = \sqrt{R_s^2 - (R_s - f)^2}$.

As shown in the Figure 4, the axial projection area can be expressed as $Sz = \arcsin \frac{b}{Rs} Rs^2 - n(R_s - f)$.

As shown in the Figure 5, the tangential projection area is $St = \theta_0\ R_\rho^2 - R_\rho^2 \sin\theta_0 \cos\theta_0$.

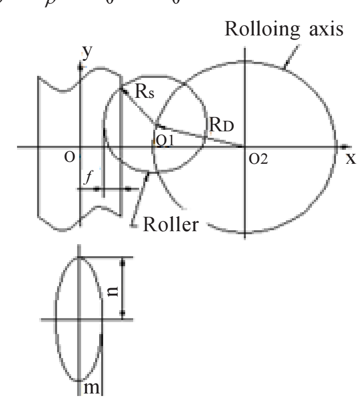


Figure 3. Radial projective area schematic of play rounds with blank contact area

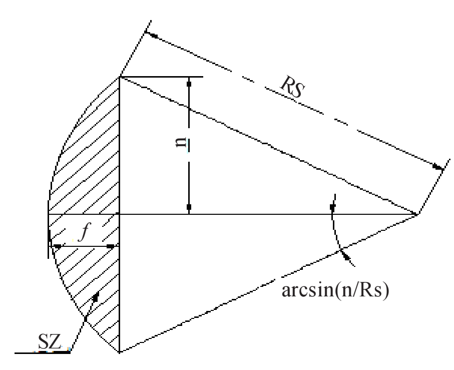


Figure 4. Axial projective area scharcsin (n/Rs)ematic of play rounds with blank contact area

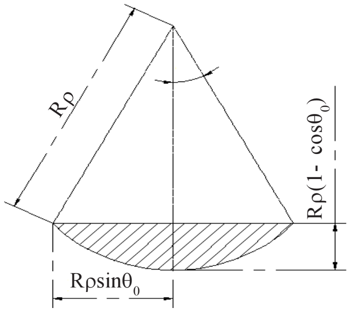


Figure 5. Tangential projective area schematic of play rounds with blank contact area

3.2.3 Deforming component force

The roll-beating force acting on the contact zone between the roller and work can be decomposed into radial component force P_r, axial component force P_z and tangential component force P_t, they can be expressed as:

$$\begin{cases} P_r = \bar{\sigma}_c Sr \\ P_z = \bar{\sigma}_c Sz \\ P_t = \bar{\sigma}_c St \end{cases} \qquad (11)$$

Among those, as the figure of roller is an arc, taking the groove shaped in the blank during once roll-beating as axial symmetry, then the forces along the two axial sides of the groove will be equal while the directions are opposite, the axial component force will be very small. Thus the axial component force can be neglected and the radial and tangential component forces will be mainly considered.

The deforming force is an requisite mechanics parameter for determining the equipment capacity, designing tool and mould correctly, making reasonable process planning and blank shape & dimensions. It will determine the stiffness of the experimental equipment and strength of the parts, selecting of roller bearing and material, thus it must be strictly controlled. Whereas in the process of determining the deforming force above, some factors such as ratio of strain are neglected, which cannot well reflect some features of the cold roll-beating, such as high-speed rotating, so the obtained results should be modified by simulation or practical experiments.

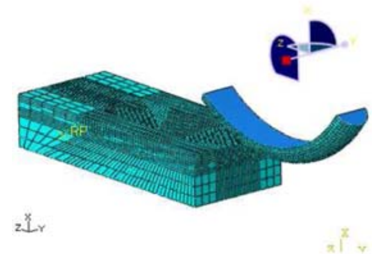


Figure 7. Geometric model of high-speed cold roll-beating

4. FEA modeling and simulating

Based on the analytical result, the FEA model of high-speed cold roll-beating is built to simulate the deforming force under different technology parameters. In simulating the high-speed cold roll-beating, the emphasis is to simulate the local deforming caused by the impacting effect. Relative to the whole blank, the plastic deforming zone is minimal. In the paper, size of the blank is 30mm × 12mm × 6mm, with ABAQUS/Explicit used, the built FE geometry model is shown in the Figure 7.

Meshing, selection of the material model, defining of the contact conditions and boundary conditions are listed in the Table 2.

The stress nephogram in a single roll-beating is shown in the Figure 8, and the corresponding deforming force is shown in the Figure 9.

5. Determining the correction item

As the radial component force P_r is much more bigger than the tangential one P_t, impact on the equipment mainly comes from P_r. Whereas in the analytical process, the process parameter n_r was not better considered, in this paper, based on the simulation results, parameter regression analysis are carried out, the roller rotation speed n_r and beating reduction f are add to the P_r expression by form of correction coefficient to make the

Meshing	work	Grid type：C3D8R
		Unit number：105930
	roller	Discrete rigid body
Material model	work	Model: rotation solid metal plastic model
		LY12 (Youg modulus: 70 GPa, Poisson ratio: 0.33, Density: 2800 kg/m^3)
	roller	Model: 3-D analytical rotation rigid shell
Contacting condition	Surface-to-Surface	
Boundary condition	work	Constraining the 6 DoFs of the inner surface
	roller	Rotating velocity is 209.44 rad/s(2 000 r/min)

Table 2. Meshing, selecting the material model, defining the contact and boundary conditions

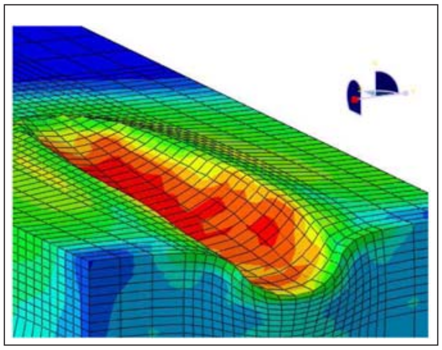


Figure 8. Mises stress nephogram of the work

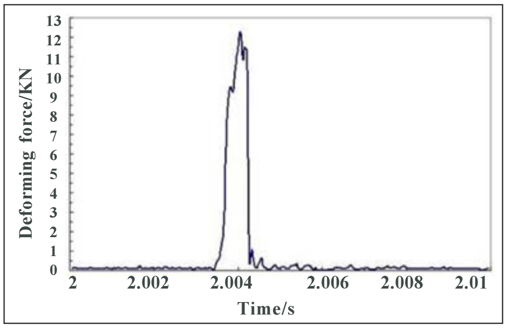


Figure 9. Curve of force

expression more better reflect the practical, so the corrected radial component deforming force is $C \times P_{rmax}$.

Let the regression model of the correction coefficient is

$$C = n_0 f^{n_1} n_r^{n_2} \tag{12}$$

Where, n_0 is a constant, n_1, n_2 are corresponding partial regression coefficients.

The analytical values and simulation results are shown in the Table 3.

Taking logarithm of the two sides of the regression model above

$$\ln C = \ln n_0 + n_1 \ln f + n_2 \ln n_r \tag{13}$$

Let $\ln C = Y$, $\ln f = X_1$, $\ln n_r = X_2$, then

$$Y = B_0 + X_1 B_1 + X_2 B_2 \tag{14}$$

The results of taking logarithm of the analytical values and simulation results are listed in the Table 4.

No.	*X1*	*X2*	*Y*
1	-0.693147	6.907755	0.038307
2	-0.693147	7.600902	0.045715
3	-0.693147	8.006368	0.051469
4	0	7.600902	0.017759
5	0	8.006368	0.022214
6	0	6.907755	0.014907
7	0.4054651	8.006368	0.013399
8	0.4054651	6.907755	0.000435
9	0.4054651	7.600902	0.006506

Table 4. The natural logarithm of Analytical value of the deformation force and simulation results

The equations to be solved can be expressed in matrix as following.

$$XB = Y \tag{15}$$

Where

$$X = \begin{bmatrix} 1 & -0.693147 & 6.907755 \\ 1 & -0.693147 & 7.600902 \\ 1 & -0.693147 & 8.006368 \\ 1 & 0 & 7.600902 \\ 1 & 0 & 8.006368 \\ 1 & 0 & 6.907755 \\ 1 & 0.405465 & 8.006368 \\ 1 & 0.405465 & 6.907755 \\ 1 & 0.405465 & 7.600902 \end{bmatrix} \quad Y = \begin{bmatrix} 0.038307 \\ 0.045715 \\ 0.051469 \\ 0.017759 \\ 0.022214 \\ 0.014907 \\ 0.013399 \\ 0.000435 \\ 0.006506 \end{bmatrix}$$

$$B = \begin{bmatrix} B_0 \\ B_1 \\ B_2 \end{bmatrix}$$

The obtained equation is

$$Y = -0.0543 - 0.0354 X_1 + 0.0099 X_2 \tag{16}$$

No.	Reduction	Roller rotation speed	Maximum analytical value of radial force	Maximum simulation value of radial force	*C*
	f (mm)	*nr* (r/min)	P_{rmax} (*N*)	P_{rmax} (*N*)	
1	0.5	1000	7119	7397	1.039050428
2	0.5	2000	7119	7452	1.046776233
3	0.5	3000	7119	7495	1.052816407
4	1.0	2000	15181	15453	1.017917133
5	1.0	3000	15181	15522	1.022462288
6	1.0	1000	15181	15409	1.015018773
7	1.5	3000	22981	23291	1.013489404
8	1.5	1000	22981	22991	1.000435142
9	1.5	2000	22981	23131	1.006527131

Table 3. Analytical value of the deformation force and simulation results

Then the correction item can be obtained as following.

$$C = 0.9471 f^{-0.0354} n_r^{0.0099} \qquad (17)$$

The corrected regression mode is as following.

$$Pr = 0.9471 f^{-0.0354} n_r^{0.0099} \bar{\sigma}_c Sr \qquad (18)$$

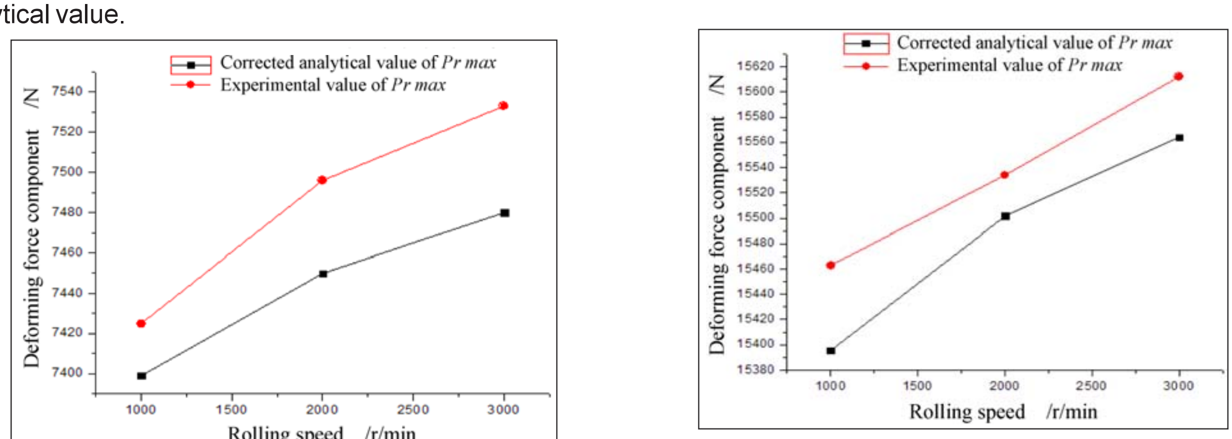
Where, $f \in [0.5, 1.5]$, $n_r \in [1000, 3000]$.

6. Experiment of the high-speed cold roll-beating

To verify the corrected regression model of the deforming force, cold roll-beating experiments are carried out with the self-made experimental equipment. The work material is LY12. The cold roll-beating forming experiments are carried out with self developed cold roll-beating equipment. As is shown in the Figure 10, measuring system of deforming force consists of special strain dynamometer and NEC data logger RA1200.

Figure 10. Experimental device

Sampling frequency is set as 5000Hz in measuring process, Parameters such as rolling reduction, feed rate and rolling speed are corresponding to the values of finite element simulation. Considering the repetitiveness of the cold roll-beating, 3 experiments under the same process condition are carried out, and the averaging value of the results are taken to be compared with the corresponding analytical value.



(a) f = 0.5mm

(b) f = 1mm

Figure 11. Comparison of experimental values and corrected analytic values of P_{rmax}

Comparisons of the peak value of the radial component deforming forces obtained from experiments and analytical expression are shown in the Figure 11. It can be seen that the two results agree well, which shows the accuracy and reliability of the corrected analytical model of the deforming force.

7. Conclusion

(1) Slab method is used to solve the analytical value of the deforming force of high-speed cold roll-beating, considering the forming process is of high speed, transient, high impacting and big deforming, some assumptions are made while using slab method, which results the obtained results are of certain limits and cannot well reflect the practical forming. Based on this, the analytical expression is corrected according to the simulation results, the corrected analytical forces can agree with the experimental results well, which shows the validity of the corrected analytical expression.

(2) Experiments are carried out with the self developed cold roll-beating equipment, and the deforming force is measured to verify the corrected analytical expression of the deforming force, at the same time which will provide guidance for cold roll-beating of complex functional surfaces. In this paper, cold roll-beating of plate blank is studied, further study should focus on the deforming forces and even forming equipments development of cold roll-beating of some complex functional surfaces such as lead screw, spline and gear, and so on.

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