JOURNAL OF ENGINEERING SCIENCES
ЖУРНАЛ ІНЖЕНЕРНИХ НАУК
ЖУРНАЛ ИНЖЕНЕРНЫХ НАУК
Web site: http://jes.sumdu.edu.ua
DOI: 10.21272/jes.2019.6(2).e5 Volume 6, Issue 2 (2019)

Numerical Experiment for the Calculation of Normal Contact Stress in the Deformation Center when Rolling a Metal Strip

Yavtushenko A. V.[1*], Protsenko V. M.[1], Bondarenko Y. V.[1], Kirichenko A. G.[1], Ping F. Y.[2]

[1] Zaporizhzhia National University, 226 Soborny Ave., 69006 Zaporizhzhia, Ukraine;
[2] Fujian Xiangxin Co. Ltd, Fuzhou, Fujian, China

Article info:
Paper received: September 4, 2019
The final version of the paper received: December 1, 2019
Paper accepted online: December 6, 2019

***Corresponding Author's Address:**
znu.kafomt@gmail.com

Abstract. The possibility of application of the program complex called Mathcad Prime 5 for calculation of normal contact stresses in the center of deformation during cold rolling of the strips is considered. The algorithm, the block-scheme and the computer program of calculation of the normal contact stresses during rolling of the strips on the reverse mill 1680 PJSC "Zaporizhstal" are developed. The epures were constructed and a comparative analysis of the formulas used to calculate the normal contact stresses in the deformation center was carried out. Received calculation data in Mathcad Prime 5 coincides with the literary data, which has practical value for both educational process and research and design work. Based on the analysis of the contact stress epures, it can be concluded that the most accurate calculation of the total metal pressure on the rolls during cold rolling is possible only when the formulas used ещ consider the change in the forced yield strength in the deformation center by the law of a straight line or the parabolic law.

Keywords: cold rolling strips, normal contact stress, deformation center, computer program, forced yield strength.

1 Introduction

The theory and practice of cold rolling have a long history of development. With the efforts of many researchers, theoretical and empirical dependencies between the basic parameters have been found that influence the process of cold rolling and are the basis for the design of the created cold rolling mills and mills that are being designed. These dependencies were not designed for the use of computer technology, so they are mostly presented in an explicit way and, in some cases, as nomograms.

The availability of ready-made formulas has its positive aspects, but with the use of computer technology, more opportunities for research and calculation and theoretical work appear. Sometimes the complexity of mathematical expressions does not allow us to solve the equations obtained. This can be avoided by having a computer-based numerical calculation program in place, that is, a numerical experiment method.

2 Literature Review

The aim of the study is the development of an algorithm and computer programs that calculate the normal contact stress in the deformation center during cold rolling of the strips on the reversed mill 1680 PJSC "Zaporizhstal" with the help of the software complex Mathcad Prime 5. Another aim is the comparative analysis of the formulas, which are used to calculate the normal stress in the deformation center.

The application of a modern computer program determines the relevance and practical significance of this article for both the educational process and research and design work.

A considerable number of works [1–10] were devoted to the issue of calculating the normal contact stresses in the deformation center during the rolling of the strips.

The calculation of normal contact stresses during rolling of the thin strips can be performed using the formulas of A. I. Tselikov [4–7]:

for the zone of slippage on the entry side

$$p_x = \frac{K_0}{\delta} \cdot \left[(\xi_0 \cdot \delta - 1) \cdot \left(\frac{h_0}{h_x} \right)^{\delta} + 1 \right]; \quad (1)$$

for the zone of slippage on the delivery side

$$p_x = \frac{K_1}{\delta} \cdot \left[(\xi_1 \cdot \delta + 1) \cdot \left(\frac{h_x}{h_1} \right)^{\delta} - 1 \right], \quad (2)$$

where p_x – normal contact stress, MPa; h_0 and h_1 – initial and final thickness of the strip, mm; h_x – thickness of the strip in the arbitrary intersection of the deformation center, mm; ξ_0 and ξ_1 – coefficients of the back and front tension.

In these equations the constant coefficients are determined by the formulas:

$$\delta = \frac{2 \cdot f \cdot l_\partial}{\Delta h}; \quad \xi_0 = 1 - \frac{\sigma_0}{K_0}; \quad \xi_1 = 1 - \frac{\sigma_1}{K_1},$$

where σ_0 and σ_1 – front and back tension, MPa; K_0 and K_1 – forced yield strengths before and after rolling in MPa ($K_0 = 1.15 \cdot \sigma_{0.2}^{(0)}$; $K_1 = 1.15 \cdot \sigma_{0.2}^{(1)}$); $\sigma_{0.2}^{(0)}$ and $\sigma_{0.2}^{(1)}$ – conditional yield strengths before and after rolling, MPa; Δh – absolute compression, mm; l_d – length of deformation center, mm; f – coefficient of friction.

The determination of the total metal pressure on the rolls by formulas (1), (2) is the most accurate, which has been confirmed by numerous experiments [4–7]. However, the use of these formulas, taking into account the law of the yield strength change in the deformation center depending on the compression, leads to cumbersome final formulas, which are inconvenient for practical calculations.

Considering $K = p_x$, formulas (1), (2) are simplified to the form [7]:

– for the zone of slippage on the entry side:

$$p_x = \xi_0 \cdot K_0 \cdot \left(\frac{h_0}{h_x}\right)^{\delta - 1}; \quad (3)$$

– for the zone of slippage on the delivery side:

$$p_x = \xi_1 \cdot K_1 \cdot \left(\frac{h_x}{h_1}\right)^{\delta + 1}; \quad (4)$$

The obtained formulas are extremely simple, but they do not sufficiently take into account the change in yield strength during the deformation process.

For more accurate accounting for the change in the forced yield strength in the deformation canter from K_0 to K_1, the following equations are obtained, assuming that the change in the yield strength occurs by the law of a straight line [7]:

– for the zone of slippage on the entry side:

$$p_x = \left[(K_0 - \sigma_0) + \frac{(K_1 - K_0) \cdot h_0}{\Delta h \cdot \delta}\right] \cdot \left(\frac{h_x}{h_0}\right)^{1-\delta} - \frac{(K_1 - K_0) \cdot h_x}{\Delta h \cdot \delta}; \quad (5)$$

– for the zone of slippage on the delivery side:

$$p_x = \left[(K_1 - \sigma_1) - \frac{(K_1 - K_0) \cdot h_1}{\Delta h \cdot \delta}\right] \cdot \left(\frac{h_x}{h_1}\right)^{1+\delta} + \frac{(K_1 - K_0) \cdot h_x}{\Delta h \cdot \delta}; \quad (6)$$

In fact, the change in yield strength in the process of deformation occurs by parabolic law. Taking this into account, the following equations are obtained [7]:

– for the zone of slippage on the entry side:

$$p_x = \left[\xi_0 \cdot K_0 + 2\frac{(K_1 - K_0)}{\Delta h^2} \cdot h_0 \cdot \left(\frac{h_0}{\delta + 1} - \frac{h_1}{\delta}\right)\right] \cdot \left(\frac{h_x}{h_0}\right)^{1-\delta} - -2\frac{(K_1 - K_0)}{\Delta h^2} \cdot h_x \cdot \left(\frac{h_x}{\delta + 1} - \frac{h_1}{\delta}\right) \quad (7)$$

– for the zone of slippage on the delivery side:

$$p_x = \left[\xi_1 \cdot K_1 - 2\frac{h_1^2}{\delta \cdot (\delta - 1)} \cdot \frac{(K_1 - K_0)}{\Delta h^2}\right] \cdot \left(\frac{h_x}{h_1}\right)^{1+\delta} + +2\frac{(K_1 - K_0)}{\Delta h^2} \cdot h_x \cdot \left(\frac{h_x}{\delta - 1} - \frac{h_1}{\delta}\right) \quad (8)$$

In order to compare the results of the calculation of normal contact stresses for all four considered formulas (1)–(2), (3)–(4), (5)–(6), and (7)–(8) in accordance with the real modes of compression on the reverse mill of 1680 PJSC “Zaporizhstal”, an algorithm and a program for the calculation in Mathcad Prime 5 software complex [11] were developed.

3 Research Methodology

In order to determine the values of the pressure in an arbitrary intersection of the deformation center, a calculation algorithm has been developed, which is shown in the block diagram of Figure1. The scheme relates to the calculation of formulas (1), (2); other formulas are calculated using a similar scheme.

The deformation center is divided into a series of intersections (from 0 to k). In each intersection, the current height of the strip h is determined, which is compared with the height of the strip in the neutral intersection h_H. The height h_H is determined by the condition of the equality of pressures in this intersection from the zones of slippage of the entry and delivery sides. For example, when calculating the formulas (1)–(2), to find h_H the equation is solved:

$$\frac{K_0}{\delta}\left[(\xi_0 \cdot \delta - 1) \cdot \left(\frac{h_0}{h_н}\right)^{\delta} + 1\right] - \frac{K_1}{\delta}\left[(\xi_1 \cdot \delta + 1) \cdot \left(\frac{h_н}{h_1}\right)^{\delta} - 1\right] = 0. \quad (9)$$

Similarly, h_H is found by calculating formulas (3)–(8).

By changing the different parameters (compression, friction coefficient, a diameter of the rolls, back and front tension coefficient) and dividing the deformation center into any number of intersections, it is possible to numerically determine the influence of each of the above factors on the distribution of normal contact stresses.

The calculation was performed in the Mathcad Prime 5 software complex, according to the block diagram shown in Figure 1. The deformation center was divided into 20 sections (indexes “k” and “i") and in each section, normal contact stresses were calculated: P_0 – for the zone of slippage on the entry side and P_1 – for the zone of slippage on the delivery side.

Table 1 presents the parameters of the Steel 1008 rolling modes on the reverse mill 1680 PJSC "Zaporizhstal" (as an example, only 4 passes out of 11 are given).

The program and the course of calculating the normal contact stresses in the deformation center in 20 sections according to formulas (1), (2) for the 1st rolling pass on the reverse mill 1680 in the Mathcad Prime 5 software complex are shown in Figure 2.

Table 1 – Table captions should be placed above the tables

Name of the parameters	Pass number			
	I	II	IV	XI
The thickness of the strip, mm				
initial h_0	3.05	2.45	1.95	0.9
final h_1	2.45	2.05	1.76	0.8
Absolute compression Δh, mm	0.60	0.40	0.19	0.1
The diameter of the working rolls D, mm	490	490	490	490
Coefficient of external friction f	0.1	0.1	0.1	0.1
Relative deformation ε, %	19.7	16.3	9.7	11.1
Yield strength, MPa				
before rolling σ_0	410	790	1040	1330
after rolling σ_1	790	990	1140	1340
Forced yield strength, MPa				
before rolling k_0	471.5	908.5	1196	1529.5
after rolling k_1	908.5	1138.5	1311	1541
Tension coefficient:				
back ξ_0	1	0.98	0.988	0.985
front ξ_1	0.98	0.97	0.976	0.979
Coefficient δ	4.041	4.950	7.181	9.899
Horizontal projection l_d of the length of the capture arc, mm	12.12	9.90	6.82	4.95

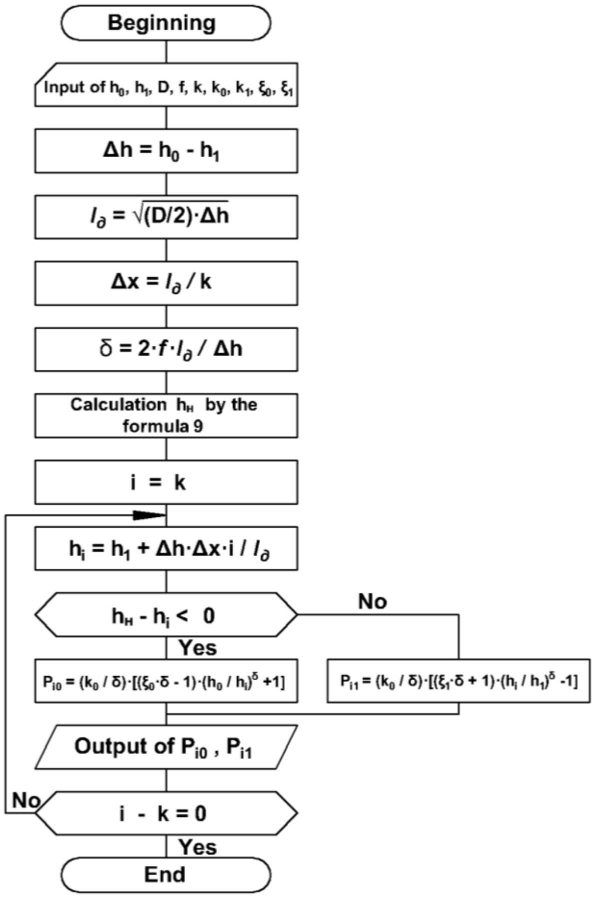

Figure 1 – A block-scheme of calculation of contact stresses during longitudinal rolling of the strips

At the same time, the simplification conducted during the derivation of the differential equation of equilibrium leads to relatively simple formulas, taking into account the change in the forced yield strength, both by the law of a straight line and parabolic law.

4 Results

According to the obtained calculation data, the epures of normal contact stresses along the length of the deformation center have been built and shown in Figure 3. The obtained diagrams coincide with those reported in the literature [6, 7].

The area of the epure is the total pressure of the metal on the rolls per width unit of the rolling strip. The area of the epures was determined as follows. All the curves of Figure 3 were plotted on a single graph in Mathcad. Then, these graphs were redrawn and the area of the epures was determined in the software complex AutoCAD Mechanical 2019.

Comparison of the areas of the normal contact stress epures, obtained by simplified formulas (3), (4) and more accurate equations of A. I. Tselikov (1), (2), shows that these areas are almost exactly the same: their maximum difference is no more than 5 %. Therefore, the simplified formulas are equivalent to the accuracy of determining the value of the normal contact stress.

5 Discussion

From the above epures, it is noticeable (Table 2) that the maximum difference of their areas by the straight-line law of change of the forced yield strength in the deformation center reaches 29 %, and 43 % by the parabolic law, especially in the first passes, when the metal is intensively hardened.

Based on the analysis of the contact stress epures, it can be concluded that the most accurate calculation of the total metal pressure on the rolls during cold rolling is possible only when the formulas used to consider the change in the forced yield strength in the deformation center by the law of a straight line or the parabolic law.

In this case, the straight-line law of change of the forced yield strength can be used with small compressions. In other cases, such formulas, which take into account the change in the forced yield strength by parabolic law, should be used.

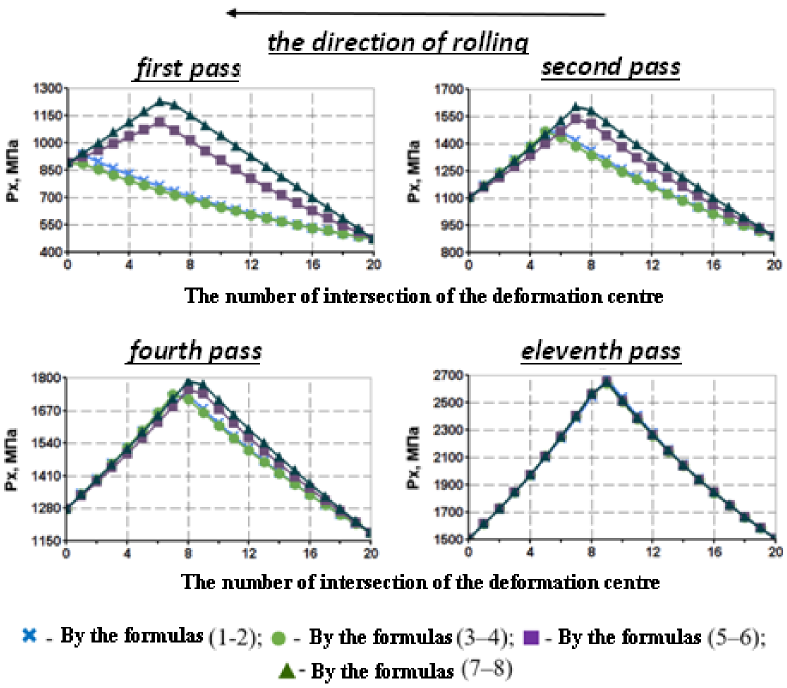

Figure 3 – Epures of normal contact stresses in the passes of a reverse rolling mill 1680

Table 2 – The areas of the normal contact stress epures according to Figure 3

Pass	Epure area, mm^2, obtained by the formulas:				The relative difference of the areas of the epures in %, obtained by the formulas			
	(1), (2)	(3), (4)	(5), (6)	(7), (8)	(1), (2)	(3), (4)	(5), (6)	(7), (8)
I	2346.6	2258.6	3020.8	3361.7	0.00	–3.75	28.73	43.26
II	6629.3	6587.5	6998.3	7334.0	0.00	–0.63	5.57	10.63
IV	8871.8	8829.4	8956.2	9143.6	0.00	–0.48	0.95	3.06
XI	13548.9	13487.1	13566.5	13573.0	0.00	–0.46	0.13	0.18

6 Conclusions

The algorithm, the block-diagram and the computer program of calculation of normal contact stresses in the deformation center during cold rolling of the strips at the reverse mill 1680 PJSC "Zaporizhstal" have been developed with the help of Mathcad Prime 5 software complex. The results of the calculations coincide with the literature data. The epures were constructed and a comparative analysis of the formulas used to calculate the normal contact stresses in the deformation center was performed. It is shown that the most reliable results can be obtained by using formulas that take into account the change in the forced yield strength in the deformation center, according to the parabolic law.

References

1. Panjkovic, V. (2014). *Friction and the Hot Rolling of Steel* (2nd ed.). Boca Raton, FL: CRC Press.
2. Lee, W., Kwak, J., Park, C. (1996). A new approach to predict rolling forces in the tandem cold rolling mill. *In Proc. 2nd International Conference on Metal Rolling Processes*. London, pp. 473–477.
3. Ginzburg, V., Ballas, R. (2000). *Fundamentals of Flat Rolling.* Marcel Dekker, New York.
4. Hensel, A., Spittel, T. (1982). *Kraft-und Arbeitsbedarf bildsamer Formgebungs-verfahren.* VEB Deutscher Verlag fur Grundstoffindustrie, Leipzig.
5. Nikolaev, V. (2018). *Napryazheniya, deformatsii i sluzhba valkov v kleti kvarto.* Monografiya. ZGIA, Zaporozhe.
6. Nikitin, G. (2009). *Teoriya nepreryivnoy prodolnoy prokatki.* Uchebnoe posobie. MGTU im. Baumana, Moscow.
7. Himich, G. (1972). *Mehanicheskoe oborudovanie tsehov holodnoy prokatki.* Mashinostroenie, Moscow.
8. Zabelin, I., Protsenko, V. (2003). Status of non-ferrous metal industry in Ukraine and problems in its development. *Metallurgicheskaya i Gornorudnaya Promyshlennost*, Issue 4, pp. 75–78.

9. Sereda, B., Kruglyak, I., Zherebtsov, A. and Belokon, Y. (2011). The influence of deformation process at titan aluminides retrieving by SHS-compaction technologies. *Metallurgical and Mining Industry,* Vol. 3, pp. 59–62.
10. Vasilchenko, T., Yavtushenko, G., Bondarenko, Y., Belokon, Y. (2015). Calculation of planetary drive of mechanical press. *Metallurgical and Mining Industry,* Vol. 7 (12), pp. 178–182.
11. Shestakov, N. (2008). Raschetyi protsessov obrabotki metallov davleniem v Mathcad (reshenie zadach energeticheskim metodom). Uchebnoe posobie. MGIU, Moscow.

УДК 621.771:514.18

Числовий експеримент з розрахунку нормальних контактних напружень в осередку деформації при прокатуванні штаб

Явтушенко О. В.[1], Проценко В. М.[1], Бондаренко Ю. В.[1], Кириченко О. Г.[1], Пінг Ф. Й.[2]

[1] Запорізький національний університет, пр. Соборний, 226, 69006, м. Запоріжжя, Україна;
[2] ТОВ «Фуцзянь Сянгсін», Фужоу, Фуцзянь, Китай

Анотація. У статті розглянуто можливості застосування програмного комплексу “MathCAD Prime 5” для розрахунку нормальних контактних напружень в осередку деформації при холодному прокатуванні штаб. Розроблено алгоритм, блок-схему і комп’ютерну програму розрахунку нормальних контактних напружень під час прокатування штаб на реверсивному стані 1680 ПАТ «Металургійний комбінат «Запоріжсталь». Побудовано епюри і виконано порівняльний аналіз формул, що використовують для розрахунків нормальних контактних напружень в осередку деформації. Розрахункові дані, отримані за допомогою програмного комплексу “Mathcad Prime 5”, співпадають з літературними даними, що визначає практичну значимість отриманих результатів для науково-дослідної та проектно-конструкторської робіт. Грунтуючись на аналізі епюр контактних напружень, можна зробити висновок, що найточніший розрахунок загального тиску металу на валки під час холодного прокатування реалізується у випадку, коли формули, які визначають математичну модель, ураховують змінювання вимушеної межі текучості в осередку деформації за прямолінійним або параболічним законами. При цьому прямолінійний закон змінювання вимушеної межі текучості може бути використаний лише для випадку порівняно невеликих обтиснень. У інших випадках необхідно використовувати формули, що враховують змінювання вимушеної межі текучості за параболічним законом.

Ключові слова: холодне прокаткування штаб, нормальне контактне напруження, осередок деформації, комп’ютерна програма, вимушена межа текучості.