Calculation of process parameters of pieces containing irregular lateral cuttings, which forming leads to such defect as “corrugation forming”

V V Mironenko1, Y N Larionova2

1Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia
2Irkutsk Aviation Plant (IAP), an affiliate of Irkut Corporation

Abstract. The paper considers the calculation of such parameters as deformation, thinning, stress and pressure demand of forming of irregular lateral cutting. It proposes the solution to eliminate such defect as “corrugation forming” caused by forming of this cutting representing a movable holder. It compares the results with finite element analysis of forming. The paper makes the conclusion on the possibility of applying the suggested calculation.

1. Introduction
Sheet forming is one of the main kinds of metal treatment under pressure, which allows receiving flat and spatial parts of the most diverse materials and configurations. Thin-walled structures from sheets are widely used in different products of mechanical engineering. High operational and strength properties of thin-walled parts and units made from sheets with the minimum weight predetermine their wider application in mechanical engineering. In this regard economic and high-performance production of qualitative thin-walled parts, especially parts with irregular shape, is one of the key problems of modern mechanical engineering. The improvement of existing processes of forming of sheet parts and development of their calculation method seems quite relevant.

One of irremediable defects of elastic forming is the “fold”. But the defect is preceded by the formation of corrugations or “corrugation forming” defect. If to control this process it is possible to eliminate this defect. The formation of cuttings may lead to “corrugation forming”. According to reference document [1], the “corrugation forming” defect occurs in the right part of the nomogram and as a result leads to “folds”. The technology used to eliminate this defect when using a movable holder is described [2]. For this technology there are no calculation methods of process parameters concerning forming, and traditional technologies are not effective. A part with high probability of corrugation formation is chosen to find the most efficient calculation formulas (Figure 1). Area of high-quality cuttings without corrugation C or with their fitting without under-forging H and gap P
2. Results

![Figure 1. Studied part](image1)

Theoretical studies regarding the second part [3] confirm that at such ratios the formation of corrugations is possible. Hence, it is possible to calculate the excess length for corrugations near the convex site. For this purpose there is a need to calculate the development site in this area.

The arch length from radius blend is equal (Figure 2, Formula 1):

\[ l_{rad} = \frac{\pi}{2} \cdot r = \frac{3.14}{2} \cdot 2 \text{ mm} = 3.14 \text{ mm} \]  

\[(1)\]

![Figure 2. Cutting parameters in the area of corrugation forming](image2)

The board length without radius blend equals to the difference of board height minus radius blend, i.e. 10.5 mm. The length for development is equal (Formula 2):

\[ l_{dev} = 10.5 \text{ mm} + l_{rad} = 10.5 \text{ mm} + 3.14 \text{ mm} = 13.642 \text{ mm} \]  

\[(2)\]

The development is built taking into account the radius increased by \( l_{times} \) (Figure 3).
Hence, $\Delta L$ equals [3] (see Formula (3):

$$\Delta L = \frac{\pi \gamma l_{dev}}{180} = \frac{3.14 \cdot 23.776^\circ \cdot 13.642 \text{ mm}}{180} = 5.661 \text{ mm}$$

To exclude corrugations it is recommended to use heel block. For this purpose it is necessary to calculate the reduction coefficient $K_r$ and the relative thickness of a workpiece flange $\bar{s}$ (Formula 4, Formula 5):

$$K_r = \frac{R_s}{R_b} = \frac{20.142 \text{ mm}}{6.5 \text{ mm}} = 3.099$$

$$\bar{s} = \frac{s}{l_{dev}} = \frac{0.5 \text{ mm}}{13.642 \text{ mm}} = 0.0366$$

According to these data there are recommendations on using heel blocks from [4]. However, there are no recommendations regarding traditional techniques. Nevertheless, the calculations show the formation of a big additional length, which characterizes corrugation formation.

Besides, according to traditional techniques [3] it is possible to calculate the required force for fixing corrugations (Formula 6, Formula 7):

$$q = \left| R_s \cdot 0.5 \gamma \cdot \frac{P}{R_s l_{rad}} \cdot \left( \sigma_0 + \Pi \cdot \left( \frac{l_{rad}}{R_s \gamma} \right) - 1 \right) \right|$$

where $R_s = 20.142$ mm, $R_b = 6.5$ mm, $\gamma = 23.776^\circ$, $P=80$ kG/mm$^2$, $\sigma_0 = 15$ kG/mm$^2$

$$q = \left| 20.142 \text{ mm} \cdot 0.5 \left( 23.776^\circ \right) \cdot 80 \text{ kG/mm}^2 \cdot \left( \frac{3.14 \text{ mm}}{20.142 \text{ mm} \cdot 23.776^\circ} - 1 \right) \right| = 755,923987 \text{ kG/mm}^2 = 7559 \text{ MPa}$$

This value shows the impossibility of using this formula for a part going beyond the nomogram [1]. Supposing that deformation of corrugation fixing is the main, the greatest and equals the ratio of the development area and the sum of areas by forming stages of a final part of a piece. Then let us calculate the development area in the area of corrugation forming according to Brahmagupta’s formula [5] (Figure 4, Formula 8, Formula 9):
Figure 4. Calculation of initial area

\[ S = \frac{1}{4} \sqrt{-\begin{vmatrix} a & b & c & -d \\ b & a & -d & c \\ -d & a & b & c \\ c & b & a & d \end{vmatrix}} \]  

(8)

where \( a = \gamma_{\text{rad}} \cdot R_b; b = d = l_{\text{dev}} = 10.5 \text{ mm} + \left(\pi \times r\right); c = \gamma_{\text{rad}} \cdot R_z; \gamma_{\text{rad}} = 23.776^\circ \times \frac{\pi}{180^\circ} = 0.415 \)

\[ S_5 = 0.25 \cdot \sqrt{0.0593 \cdot R_b^2 \cdot R_z^2 - 0.0297 \cdot R_b^4 + 1.7 \cdot R_b^2 \cdot r_b^2 + 22.7 \cdot R_b^2 \cdot r_b + 75.9 \cdot R_b^2 + 3.4 \cdot R_b \cdot R_z \cdot r_b^2 + 45.4 \cdot R_b \cdot R_z \cdot r_b + 152 \cdot R_b \cdot R_z - 0.0297 \cdot R_z^4 + 1.7 \cdot R_z^2 \cdot r_b^2 + 22.7 \cdot R_z^2 \cdot r_b + 75.9 \cdot R_z^2 + 3.23 \cdot 10^{-27} \cdot r_b^3 + 1.03 \cdot 10^{-25} \cdot r_b + 4.14 \cdot 10^{-25}} = 73.75047 \text{ mm}^2 \]  

(9)

Let us find the area on a piece, which will be final at corrugation fixing, where \( a_6 = \gamma_{\text{rad}} \cdot R_6; b_6 = d_6 = l_{\text{dev}} = 10.5 \text{ mm} + \left(\pi \times r\right); c_6 = \gamma_{\text{rad}} \cdot R_{6+} = R_b + r \) (Figure 5, Formula 10):

\[ S_6 = 0.25 \cdot \sqrt{0.00000191 \cdot r_b + 90.9 \cdot R_b \cdot r_b^2 + 90.9 \cdot R_b^2 \cdot r_b + 6.68 \cdot R_b \cdot r_b^3 + 5.82 \cdot 10^{-11} \cdot R_b^5 \cdot r_b + 304 \cdot R_b^5 \cdot r_b^2 + 1.46 \cdot 10^{-11} \cdot R_b^6 + 75.9 \cdot r_b^5 + 22.7 \cdot r_b^3 + 1.67 \cdot r_b^4 + 6.68 \cdot R_b^2 \cdot r_b^2 + 304 \cdot R_b \cdot r_b + 0.00000763} = 42.448 \text{ mm}^2 \]  

(10)
It is also necessary to add the area of corrugation fixing at the last stage. Supposing that two sides of these surfaces are equal to the arch length of a radius blend where \( a_5 = c_5 = \gamma_{rad} \cdot (R_b + r) \); \( b_5 = d_5 = \left( \frac{\pi}{2} \cdot r \right) \) (Figure 6, Formula 11):

\[
S_7 = 0.25 \cdot \sqrt{6.8 \cdot R_b^2 \cdot r_b^2 - 2.91 \cdot 10^{-11} \cdot R_b^3 \cdot r_b - 1.46 \cdot 10^{-11} \cdot R_b^4 + 13.6 \cdot R_b \cdot r_b^3 + 6.8 \cdot r_b^4 = 11.083 \text{mm}^2}
\]  

(11)

Then the deformation at corrugation fixing is equal (Formula 12):

\[
\varepsilon_{fix} = \left( \frac{S_5 - (S_4 + S_2)}{S_5} \right) \cdot 100\% = \left( \frac{73.750 \text{mm}^2 - (42.448 \text{mm}^2 + 11.083 \text{mm}^2)}{73.750 \text{mm}^2} \right) \cdot 100\% = 27.4\%
\]  

(12)

Next, it is necessary to calculate fixing stress. To describe the behavior of material in a plastic zone let us use the Krupkowsky law function [6]. It is the mathematical function considering strain hardening and connecting equivalent stress with plastic deformation (Formula 13):

\[
\sigma = K(\varepsilon_0 + \varepsilon_p)^n
\]

(13)

where \( K \) – mathematical constant of this material;
\( n \) – coefficient of strain hardening;
\( \varepsilon_0 \) – deformation of counting the beginning of plastic deformations.

For D16AM \( K = 324.17 \text{MPa} \); \( n = 0.2183 \); \( \varepsilon_0 = 0.0003 \) and \( \varepsilon_p = \varepsilon_{fix}/100\% \)
In our case stresses are equal (Formula 14):

$$\sigma_{pod} = 324.17 \, MPa \cdot (0.0003 + 0.274)^{0.2183} = 244.42 \, MPa$$

(14)

For verification finite element modeling in PAM-STAMP system was carried out and the natural experiment was performed. The following results are obtained (Table 1).

**Table 1. Results of modeling and natural experiment**

| Location | Equivalent Stress MPa |
|----------|-----------------------|
| 1        | 256.641               |
| 2        | 174.684               |
| 3        | 222.931               |
| 4        | 120.72                |
| 5        | 147.657               |

\[
\sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}
\]

\[
\varepsilon = \sqrt{\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2}
\]

**3. Conclusion**

As a result we see that:

- the difference between $$\sigma_{pod} = 252.627 \, MPa$$ calculated analytically and $$\sigma_{eq} = 256.641$$ makes 4.8%, so the results can be considered identical;
- the difference between $$\varepsilon_{fix} = 27.4\%$$ calculated analytically and $$\varepsilon=28.13\%$$ makes 2.7%, so the results can be considered identical.

Based on comparisons it is possible to conclude that the suggested formulas can be used to calculate deformation and stress while forming irregular cuttings going beyond the nomogram [1] into a defect zone of “corrugation forming”.

**References**

[1] OST 1.52468–80
[2] Mironenko V and Shmakov A 2018 Movable-clamp undercutting of sheet metal parts *Advances in Engineering Research Int. Conf. on Aviamechanical Engineering and Transport (AviaENT 2018) vol 158* 271–5
[3] Isachenkov E I 1967 *Rubber pressing and high-pressure liquid forming* (Moscow: Mechanical engineering) 367 p
[4] RDMU 95–77
[5] Fedorchuk M and I Pak 2005 Rigidity and polynomial invariants of convex polytopes *Duke Math. J.* 129(2) 371–404 DOI:10.1215/S0012-7094-05-12926-X
[6] PAM-STAMP 2012 User’s Guide, ESI Group 2012 pp 960
[7] Bobarika I, Demidova A and Bukhanchenko S 2017 Hydraulic Model and Algorithm for Branched Hydraulic Systems Parameters Optimization *Procedia Engineering ser. Int. Conf. on Industrial Engineering ICIE 2017* pp 1522–27
[8] Shahrai S, Sharypov N, Polyakov P, Kondratiev V and Karlina A 2017 Quality of anode Overview of problems and some methods of their solution Part 2 Improving the quality of the anode *Int. J. of Applied Engineering Res.* 11 268–78
[9] Baranov, Kondratiev V, Ershov V, Judin A and Yanchenko N 2016 Improving the Efficiency of Aluminium Production by Application of Composite Chrome Plating on the Anode Pins Int. J. of Applied Engineering Res. 22 10907–10
[10] Khusainov R, Sabirov A and Mubarakhshin I 2017 Study of Deformations Field in the Working Zone of Vertical Milling Machine Procedia Engineering ser. Int. Conf. on Industrial Engineering ICIE 2017 pp 1069–74
[11] Fabík R, Kliber J, Kubina T, Mamuzic I and Aksenov S 2012 Mathematical Modelling of Flat and Long hot rolling Based on Finite Element Methods (FEM) 51(3) (Sisak Yugoslavia: Metalurgija) pp 341–4
[12] Chumachenko E, Aksenov S and logashina I 2012 Optimization of Superplastic Forming Technology METAL 2012 Conference proceedings 21st Int. Conf. on Metallurgy and Materials pp 295–301
[13] Mokritskii, Vereshchagin V, Mokritskaya E, Pyachin S, Belykh S and Vereshchagin A 2016 Composite Hard-Alloy End Mills Russian Engineering Res. 36(12) 1030–2
[14] Kondratiev V, Rzhechitskij E, Shakhrai S, Karlina A and Sysoev I 2016 Recycling of Electrolyzer Spent Carbon-Graphite Lining With Aluminum Fluoride RegeneratioN, Metalurgist 60(5–6) 571–5
[15] Kondrat’ev V, Govorkov A, Lavrent’eva M, Sysoev I and Karlina A 2016 Description of the heat exchanger unit construction, created in IRNITU Int. J. of Applied Engineering Res. 11(19) 9979–83
[16] Sevastyanov G, Chernomas V, Marin S and Sevastyanov A 2015 Numerical Simulation Features of Continuous Casting Process Form AD31 (A (Greek Passage)31) Alloy Using Finite-Difference and Finite Element Models Non-Ferrous Metals 2 25–9
[17] Belykh S and Perevalov A 2013 Modelling of Bending Rolls of Extruded Nonsymmetric in the MSC Marc European Researcher 5–1(48) 1140–46
[18] Roschupkin V, Krupskii R, Levchuk T and N Semashko 2002 Methodical Aspects of Exciting Acoustic Emission of Magnetostriiction Russian metallurgy (Metally) 4 361–2
[19] Roschupkin V, Semashko N, Krupskii R, Kupov A and Shport V 2003 Temperature and Strain Changes in VT20 Titanium Alloy under Electric-Pulse Effect High Temperature 41(5) 633–8
[20] Pokrasin M, Semashko N, Krupskii R and Kupov A 2004 Effect of Electric-Pulse Treatment on the Dislocation Structure of OT4 Titanium Alloy”, Russian metallurgy (Metally) 6 595–600
[21] Roschupkin V, Pokrasin M, Chernov A, Sobol N, Semashko N, Krupskii R and Kupov A 2005 Deformation of VT20 and OT4 Titanium Alloys Subjected to a High-Density Pulse Current During Static Loading Rus. metallurgy (Metally) 4 350–54
[22] Erisol Y, Grechnikov F and Surudin S 2016 “Yield Function of the Orthotropic Material Considering the Crystallographic Texture Structural Engineering and Mechanics 58(4) 677–87
[23] Erisol Y, Surudin S, Shlyapugin A and Grechnikov F 2016 The End-to-End ComputeR Simulation of Casting and Subsequent Metal Forming Key Engineering Materials 685 167–71
[24] Pal-Val P, Natsik V, Pal-Val L, Loginov Y, Demakov S and Illarionov A 2014 Unusual Young’s Modulus Behavior in Ultrafine-Grained and Microcrystalline Copper Wires Caused by Texture Changes During Processing and Annealing Materials Sci. and Engineering 618 9–15
[25] Bourkine S, Korshunov E, Lognin Y, Shakhapazov E, Nassibov A and Babailov N 1999 Projection of Steel Wire Producing Technology Beyond the Continuous-Casting of an Ingot Using a Direct Combination of Casting and Metal Forming J. of Materials Processing Technology 86(1–3) 278–90