Pressure calculation for preliminary formation of undercuts prone to defect of fold type

M V Lavrentyeva and V V Mironenko
Department of Aircraft Construction and Maintenance, Institute of Aircraft Construction, Mechanical Engineering and Transport, Irkutsk National Research Technical University, 83, Lermontova str., Irkutsk, 664074, Russia
E-mail: mira.amazon@gmail.com

Abstract. The paper presents the calculation of the pressure at the first transition during the formation of the “undercuts” on which corrugation takes place. The formulas in general form for the stresses at the first transition and the required pressure depending on the length of the sweep are derived. The results with the finite element analysis of formation and field experiments are compared. The conclusions about the verification of the results are drawn.

1. Introduction
Fold is one of the most unfavorable defects that may appear during formation in sheet metal stampings.
This is explained by the fact that if this defect is on the detail, then it can not be eliminated even by the increase in the laboriousness of producing the detail (for example, a defect of undercuts type can often be eliminated by manual fixing). In this regard, the researchers pay special attention to the details on which this defect may arise. A defect of fold type is preceded by such a process as corrugation. A fold occurs if a detail is uncontrollably molded during orbital formation.
The most difficult thing is to control this process if the corrugation occurs on details with such an element as undercuts. However, there is a method to eliminate this defect and prevent the formation of defects on such details [3]. The movable clamp allows molding details of this kind and eliminating defects. However, if at the first transition we do not select the correct pressure at which preliminary formation will be performed, the height of the corrugation will be small and it will be too rigid and even the use of a movable clamp will not ensure high-quality production of the detail.

2. Results
In this article the calculation of the preliminary pressure for formation will be shown through the example of one detail. The detail for consideration is shown in Figure 1.
In order to carry out this calculation, we will express the length of the sweep, through the value of which it will have radial compression and will decrease by the length ΔL in the zone where the corrugation will be formed (Figure 2).
Let us assume that all sides decrease during fixing keeping the shown proportion at the initial moment of formation. Then, according to Brahmagupta formula [3], the area will be equal (Formula (1):)

\[ S_{\text{init.}} = \frac{1}{4} \sqrt{\begin{vmatrix} 0.322 \cdot L & 1.632 \cdot L & L & -1.632 \cdot L \\ 1.632 \cdot L & 0.322 \cdot L & -1.632 \cdot L & L \\ L & -1.632 \cdot L & 0.322 \cdot L & 1.632 \cdot L \\ -1.632 \cdot L & L & 1.632 \cdot L & 0.322 \cdot L \end{vmatrix}} = 0.25 \cdot \sqrt{17.8} \cdot L^4 \]  

(1)

In general, this formula will have the following form (Formula (2):

\[ S_{\text{init.}} = 0.25 \cdot \sqrt{L^4 \cdot (4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 + 8 \cdot t \cdot y^2 + 4 \cdot y^2 - 1)} \]  

(2)

where \( t \) - coefficient of dependence on \( L \) of the larger side of the sweep (in our case, 1.632); \( y \) - coefficient of dependence on \( L \) of the smaller side of the sweep (in our case 0.322).
Let us express the stress through the function “Krupkowsky law” [3]. In this case, we express plastic deformations as the ratio of the areas of the scan area in the corrugation region to the current corrugation area. As a result, we get (Formula (3):

\[
\varepsilon_p = \frac{S_5 - S_{init}}{S_5} = \frac{0.25 \cdot \sqrt{4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 +}}{8 \cdot t \cdot y^2 + 4 \cdot y^2 - 1}
\]

where \(K\) - mathematical constant of a given material; \(n\) - work hardening coefficient; \(\varepsilon_0\) – deformation of the start of plastic deformations; \(S_5\) - scan area at the initial moment before formation;

For D16AM \(K= 324,17\) MPa, \(n= 0.2183; \varepsilon_0=0.0003;\)

Then for the stress we have (Formula (4):

\[
\sigma = K(\varepsilon_0 + \varepsilon_p)^n = K \left( \frac{S_5 - 0.25 \cdot \sqrt{L^4 \cdot (4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 +}}{8 \cdot t \cdot y^2 + 4 \cdot y^2 - 1}}{S_5} \right)^n
\]

\[
= K \left( \frac{S_5 + S_5 \cdot \varepsilon_0 - 0.25 \cdot \sqrt{L^4 \cdot (4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 +}}}{S_5} \right)^n
\]

\[
= 324,17 \text{ MPa} \left( \frac{73.75 \text{ mm}^2 + 73.75 \text{ mm}^2 - 0.0003 \cdot 0.25 \sqrt{17.84 L^4}}{73.75 \text{ mm}^2} \right)^{0.2183}
\]

Since we are considering the initial moment of formation, the value of \(L\) changes slightly. From this it follows that the change in this function will occur in a small range. Consider the range 7.5 to \(L = 8.3582\) (Figure 3).

**Figure 3.** Stress dependence diagram from \(L\).
With the value of pressure, we can calculate the value of the required pressure at the first transition based on the fact that the formation force is distributed over the entire area of the detail (Figure 4, Formula (5) (in our case, 3116.0741mm²)).

\[
q_{rec} = \frac{\sigma \cdot S_{init}}{S_d}
\]

\[
K \left( \varepsilon_0 + \left( \frac{S_5 - 0,25 \cdot \sqrt{\frac{l^4 \cdot (4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 + 4 \cdot y^2)}{S_5}}}{S_5} \right) \right) \cdot 0,25 \cdot \sqrt{\frac{l^4 \cdot (4 \cdot t^2 \cdot y^2 - 1 \cdot t^4 + 2 \cdot t^2 + 4 \cdot y^2)}{S_5}}
\]

\[
0,25^{n+1} \cdot K \cdot \sqrt{17,8 \cdot l^4} \cdot \frac{4 \cdot S_5 + 4 \cdot S_5 \cdot \varepsilon_0 - \sqrt{17,8 \cdot l^4}}{S_5}
\]

\[
0,25^{n+1} \cdot K \cdot \sqrt{17,8 \cdot l^4} \cdot \frac{4 \cdot S_5 + 4 \cdot S_5 \cdot \varepsilon_0 - \sqrt{17,8 \cdot l^4}}{S_5}
\]

\[
\frac{S_d}{S_d}
\]

As a result we get the following diagram (Figure 5).
Figure 5. Graph of the required pressure from L for the studied detail

For example, in this case for \( L = 8 \) = the required pressure is 3.627 MPa. The stresses at this pressure in the detail according to the formula (4) are equal to \( \sigma = 159.357 \) MPa. As a result, the function for the calculation of the required pressure on the preliminary formation in general form is presented in Formula (5):

\[
q_{rec}(L) = \frac{0.25n+1-K\cdot\sqrt{17.8L^2}}{S_d} \left( \frac{4S^5+4S^5\varepsilon_0-\sqrt{17.8L^2}}{S^5} \right)
\]

In order to verify the results, finite element modeling the formation of this detail in two transitions was carried out:
- 1st transition: pre-formation with the pressure that was calculated
- 2nd transition: final molding with a movable clamp;

As a result we have:
- equivalent stresses calculated by the formula of the energy theory of strength [3].

Figure 6. Stress gradient for 1 transition

| Location | EQUIVALENT STRESS MPa |
|----------|-----------------------|
| 1        | 152.079               |
| 2        | 133.15                |
| 3        | 116.345               |
| 4        | 127.247               |
| 5        | 138.521               |

Min = 0.778  
Max = 268.699
The difference between \( \sigma = 159,357 \text{ MPa} \) (Formula (4) calculated analytically) and \( \sigma_{\text{eq1 trans}} = 152,079 \) (Figure 7) is 4.6% thus the results can be considered identical.

- The length of the sweep during corrugation (\( L = 8.064 \text{ mm.} \)) which is less than the calculated one (8.2 mm.) by 1.7% thus the results can be considered identical (Figure ).

![Figure 7. Sweep length at pressure 3,627 MPa](image)

![Molded detail](image) ![Sweep length at the first transition](image)

**Figure 8.** Detail in real experiment and the length of the sweep at the first transition
A real experiment was carried out, which also proved convergence. The sweep length was $L = 8.2$ mm, calculated analytically according to the proposed method and the length of the sweep on the real detail $L_{\text{real}} = 8.1185$ mm. (Figure 8) differed by 0.994% so the results can be considered identical.

After the second transition with a movable clamp, a detail is produced without defects [2] (Figure 9).

Figure 9. Molded detail after the second transition

3. Conclusion

As a result, the authors proposed the method for the calculation of the pressure at the first transition during the formation of undercuts on which corrugation can take place. The results of real and virtual experiments prove the adequacy of the proposed formulas.

References

[1] Govorkov A S, Lavrenteva M V and Fokin I V 2018 Mathematical modeling of making mechanical engineering products based on an information model MATEC Web of Conferences 224 02022. DOI: https://doi.org/10.1051/matecconf/201822402022

[2] Chumachenko E, Aksenov S and Logashina I 2012 Optimization of superplastic forming technology Metal 2012 – Conf. Proc., 21st int. conf. on metallurgy and materials pp 295-301

[3] 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 2015(2) 25-29

[4] Govorkov A S, Zhilyaev A S and Fokin I V 2018 Method of transition from 3d model to its ontological representation in aircraft design process J. of Phys.: Conf. Ser. 1015(3) 032046

[5] Lavrentyeva M and Govorkov A 2017 Using a discrete product model to determine the design element junctures MATEC Web of Conferences 129 03002. DOI: 10.1051/matecconf/201712903003

[6] Lavrentieva M V, Chimitov P E and Govorkov A S 2019 Development of a computer aided design system for assembly equipment of MC-21 aircraft IOP Conf. Ser.: Mater. Sci. Eng. 632 012099. DOI: 10.1088/1757-899X/632/1/012099

[7] Fedorchuk M and Pak I 2005 Rigidity and polynomial invariants of convex polytopes Duke Math. J. 129(2) 371-404. DOI: 10.1215/S0012-7094-05-12926-X.

[8] 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) 2004(6) 595-600

[9] Mironenko V V and Larionova Y N 2019 Calculation of process parameters of pieces containing irregular lateral cuttings, which forming leads to such defect as "corrugation forming" IOP Conf. Ser.: Mater. Sci. Eng. 632 012102
[10] Mironenko V V and Larionova Y N 2019 Mathematical model to calculate key parameters of forming irregular lateral cuttings on sheet articles to eliminate such defects as "under-forging" IOP Conf. Ser.: Mater. Sci. Eng. 632 012101

[11] Mokritskii B, Vereshchagin V, Mokritskaya E, Pyachin S, Belykh S and Vereshchagin A 2016 Composite hard-alloy end mills Russian Engineering Research 36(12) 1030-1032

[12] Pal-Val P, Natsik V, Pal-Val L, Loginov Y, Demakov S and Illarionov A 2016 Unusual young's modulus behavior in ultrafine-grained and microcrystalline copper wires caused by texture changes during processing and annealing Mater. Sci. Eng. A 618 9-15

[13] PAM-STAMP 2012 User’s Guide, ESI Group, 2012 – 960

[14] 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) Metalurgija (Sisak, Yugoslavia) 51(3) 341-344

[15] Khusainov R, Sabirov A and Mubarakshin I 2017 Study of deformations field in the working zone of vertical milling machine Procedia Engineering 206 1069-1074

[16] Belykh S and Perevalov A 2013 Modelling of bending rolls of extruded nonsymmetric in the msc marc European Researcher 5-1(48) 1140-1146

[17] Bourkine S, Korshunov E, Loginov 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) 278-290

[18] Sokolnikov R A, Bozheeva T V and Govorkov A S 2020 Development of methodology for formalized selection of technological operations when designing technological process manufacturing of machinery J. of Phys.: Conf. Ser. 1582(1)

[19] Roshchupkin 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 Russian metallurgy (Metally) 2005(4) 350-354

[20] Roshchupkin 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) 633-638

[21] Roshchupkin V, Krupskii R, Levchuk T and Semashko N 2002 Methodical aspects of exciting acoustic emission of magnetostriction Russian metallurgy (Metally) 4 361-362

[22] Mironenko V and Shmakov A 2018 Movable-clamp undercutting of sheet metal parts Advances in Engineering Research 158 271-275

[23] Erisov Y, Grechkinov F and Surudin S 2016 Yield function of the orthotropic material considering the crystallographic texture Structural Engineering and Mechanics 58(4) 677-687

[24] Erisov Y, Surudin S, Shlyapugin A and Grechkinov F 2016 The end-to-end computer simulation of casting and subsequent metal forming Key Engineering Materials 685 167-171

[25] Isachenkov E I 1967 Rubber and liquid forging (Moscow: Mashinostroenie) 367 p