Identification of problem parts made by longitudinal stretching when compensating for springing

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Abstract. The paper considers problem related to the compensation of springing of parts produced by longitudinal stretching. It proposes the method of eliminating this effect by replacing the shaping method with transverse stretching. A finite element simulation of transverse stretching for the selected element produced by longitudinal stretching was carried out. The analysis of results revealed elimination of negative phenomenon of springing. After changing the scheme, the nature of the workpiece movement during springing became classic. The paper describes the procedure for the geometry of the element to determine problems in the compensation of fitting related to springing. The method takes into account the geometric parameters of the curvature radii of the element in different directions and the relations between them. The criteria for identifying problem parts are presented.

1. Introduction
One of the most difficult tasks in the production of aircraft sheet parts is the manufacture of aircraft outline parts. The specifics of making these parts includes the application of a double effect. As a result, at the last stage, when the element is unbent by moving the tooling upwards, a stressed deformed state occurs that makes the workpiece spring inwardly. Hence, the compensation of springing becomes ineffective because it reduces the curvature radius of the element and as a consequence increases springing. This problem is a very serious obstacle to the application of this shaping technology.

2. Considered element
Let us consider an element made by longitudinal stretching from aluminum alloy 1163AM, which forming causes problems with the above springing compensation (Figure. 1).

Let us simulate the forming process. The software product PAM-STAMP 2G by the French company ESI Group will be used as a program for finite element analysis. The material model in the software product was set by the following parameters:
- Young modulus – 72.05 GPa;
- Poisson coefficient – 0.323;
- density – 2.6 kg/mm³;
- anisotropy coefficients $r_0^0$, $r_45^0$, $r_90^0$ – 0.534, 0.834, 0.59;
- plastic part of the flow curve is set by the Krupkowsky law function, which looks as follows (Formula 1):

(Formula 1)
\[ \sigma = K (\varepsilon_0 + \varepsilon_p)^n \]

Function constants for the material: \( K = 0.65204 \text{ GPa}, \) \( n = 0.2949, \varepsilon_{p0} = 0.0045 \)

Figure 1. Considered element

3. Replacement of the forming method with transverse stretching and compensation of its springing in fitting

In order to eliminate the negative effect of elastic response and make springing compensation effective, it is necessary to change the loading pattern during shaping. It is proposed to change the type of stretching from longitudinal to transverse because there is no shape change in two directions. With the same parameters of the material model, a simulation was conducted for transverse stretching, according to which it can be concluded that an element can be made this way (Figure 2).

A springing gradient was calculated for the area of a workpiece in contact with fitting and in this case the springing is aimed at reducing curvature (Figure 3, Figure 4). As a result, the compensation becomes effective since the curvature of the element increases, and hence, the deformation should increase or at least not change. In our case, the deformation remained constant, therefore, the springing is constant and will be equal to 0 iterations (Figure 5 a). The shape will change and become similar to the element shape. This value should decrease with proper compensation progress (Figure 5 b).
Maximum deformation – 19.5%, less than 20%

Minimum thickness (blue) – 1.217 mm, thinning 18%, less than 20%

a – distribution of deformation and thickness on a workpiece

Maximum deformation – 10.6%, less than 20%

Minimum thickness (blue) – 1.338 mm, thinning 10.8%, less than 20%

b – distribution of deformation and thickness in the element contour on a workpiece

there are no blue zones on the workpiece and parts indicating the presence of dangerous deformation zones in which cracks can occur

c – Keller-Goodwin limit deformations diagram in the element contour of a workpiece and on the workpiece as a whole

**Figure 2.** Results of transverse stretching simulation
Figure 3. Distribution of transverse stretching springing

a – spring distribution for the area of the workpiece in contact with fitting, the maximum distance of the workpiece from the fitting surface is 28.8 mm

b – area of the workpiece in contact with fitting before and after the springing effect, white surface – workpiece after elastic response (springing caused the edges of the workpiece to deflect outward)

Figure 4. Results of fitting compensation for transverse stretching

a – color distribution showing fitting at different iterations of springing compensation

b – configuration of fitting options according to springing compensation iterations in one section
a – distribution of plastic deformation for the area of the workpiece in contact with fitting according to iterations of spring compensation (plastic deformation decreases)

b distribution of springing for the area of the workpiece in contact with fitting according to iterations of springing compensation (the value decreases, i.e. the shape becomes similar to the shape of the element)

**Figure 5.** Results of transverse stretching compensation

**Figure 6.** Sections to define the curvature radius (red line indicates section for analysis)
All of the above indicates the correct course of the compensation process and the elimination of the negative springing effect.

4. **Identification of elements with problem shape made by stretching for springing compensation**

However, it remains a problem to identify the element with a problem shape. Using the example of the element to simulate the shaping process, let us analyze its shape for curvature. To do this, let us split it into sections in places of pronounced change of the curvature radius. As a result, we have 4 sections (three in one direction and one in the other) (Figure. 15). Using the example of one section, let us calculate the curvature radius of (Figure. 6).

To calculate, let us move the section to the origin of the coordinate system and plot the function.

![Graphs](image_url)

**Figure 7.** Section for analysis

Since a curve is similar in appearance to a parabola, it makes sense to find its function. To do this, let us use the least square method in setting the approximation to a power function \(a \cdot x^2 + b \cdot x + c\) [13]. As a result, we have the following function describing our section (Formula 1):

\[
y(x) = -0.00028297731220943 \cdot x^2 + 0.47393259942476196 \cdot x + 4.589376870719401
\]  

(1)

The graphic view of the two graphs shows that the match is not ideal, therefore, it is necessary to evaluate the correlation (Figure. 8). To do this, let us calculate the Pearson coefficient [11]. The Pearson coefficient eventually turned out to be 0.763. According to the Chaddock table [10] we estimate the correlation force and we see that it is high, i.e. the error between functions is not significant.

![Graphs](image_url)

**Figure 8.** Function graphs
Now we need to calculate the curvature parameter of the function using the formula 2 [10]:

\[
K = \frac{y'}{(1 + (y')^2)^{3/2}}
\]  

(2)

The first derivative has the form \(-0.00028297731220943 \cdot x + 0.47393259942476196\), and the second is equal to the scalar value \(-0.00056595462441886\). The function for curvature calculation takes the form blow (Formula 3):

\[
K = \frac{-0.00056595462441886}{(1 + (-0.00028297731220943 \cdot x + 0.47393259942476196)^2)^{3/2}}
\]  

(3)

Having calculated its values in the range from 0 to 1670.71 (i.e. in the dimensions along the x-axis), we take the minimum value modulo. As a result, we get 0.0004176. The curvature radius is equal to \(R = 1/K\) [17]. Hence, we have the curvature radius equal to 2394.636. For verification in the Siemens NX 12 CAD system, let us build a curvature radius envelope. Since the envelope is not constant (it has a pronounced “hole”, i.e. there it is necessary to make a denser sample), we take the average value of the curvature radius according to the values indicated below (Figure. 9). As a result, we have the curvature radius of 2340.2 and the difference between the calculated value (2394.636) according to the proposed method is not more than 3%.

Maximum value – 2996.2250
Minimum value – 960.632

Interchange values from maximum to minimum epure 2718.753; 2552.354; 2475.909

\(a\) – radius of curvature diagram constructed in Siemens NX 12 with maximum and minimum value

\(b\) – radius of curvature diagram constructed in Siemens NX 12 with intermediate values in the range of interest

**Figure 9.** Radius of curvature for section in Siemens NX 12

For the remaining sections, according to the proposed method, the curvature radii were found (Figure. 10).
Now it is necessary to relate curvature in one direction and another alternately. In our case, there are more sections in one direction, therefore, it is previously necessary to take the arithmetic mean of these curvature radii and then deal with this value. As a result, we get the value of two coefficients, the difference between which in percentage will show the curvature value. As a result, we get (Formula 4):

$$E_1 = \frac{64248682}{(2394636 + 27938766 + 14883386)} = 2.887;$$

$$E_2 = \frac{(2394636 + 27938766 + 14883386)}{64248682} = 0.346$$

Figure 10. Section curvature radii according to the proposed methodology

Now let us calculate the percentage difference between these values taking the maximum value as the basis [16]. As a result, we obtain the value of the curvature proportionality in the element $\Psi = 88\%$. Having analyzed other elements manufactured by longitudinal stretching (with which there are no similar problems with springing compensation), the value of curvature proportionality is more than 90% (Figure 11).

Figure 11. Values of curvature proportionality
If all three values (88%, 95%, 99%) are analyzed (from the point of view that the first value is critical and it is not recommended to go below it) and a mathematical expectation is found, it will be 94%. Variance and standard deviation are 20.667 and 4.546%, respectively. Based on this, it can be assumed that the threshold value after which the proportionality value indicates compensation problems will be equal to the mathematical expectation minus the mean square deviation, i.e. 94% – 4.546% = 89.454% [11].

As a result, in the general form of the formula for the coefficients of the curvature ratio and the value of the curvature proportionality will take the following form (Formula 5):

$$
\begin{align*}
\Xi_1 &= \frac{\sum_{i=1}^{n} R1_i}{n}; \\
\Xi_2 &= \frac{\sum_{i=1}^{n} R2_i}{n}; \\
\Psi &= \frac{\max(\Xi_1, \Xi_2) - \min(\Xi_1, \Xi_2)}{\max(\Xi_1, \Xi_2)} \cdot 100\%.
\end{align*}
$$

(5)

where R1, R2 – curvature radii in different directions of the element of n- and i-section (respectively); i, n – number of sections in different directions of the element.

5. Conclusion
As a result, the paper describes the problem in springing compensation in the fitting of parts manufactured by longitudinal stretching. It was proposed to solve this problem by replacing the shaping scheme with transverse stretching. The study suggests the method of assessing the element on problems with springing compensation. A threshold value of the suggested criterion is shown, which helps to determine whether the element will have problems with springing compensation.

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