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A New Equation to Determine the Springback in the Bending Process of Metallic Sheet

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Summary

In this work, a new equation to predict the springback in the bending and rolling processes of metallic sheet is presented. This equation has been experimentally applied in the design of a wood truncated cone to form an aluminum sheet truncated cone. Kalpakjian's equation was also applied but Damian's equation has given the best performance.

Introduction

In the one-axial tension test of a metallic specimen, its initial behavior is evaluated according to Hooke's Law until the applied stress is equalized to the yield strength of the specimen material. If the yield strength is exceeded, the material is permanently formed. If the stress is withdrawn, the specimen length is contracted due to the material springback [1-2]. This same phenomenon is observed when a metallic sheet is bent between male and female bending dies (see Figures 1 and 2). The basic bibliography for manufacturing processes [2-4] quotes that this said elastic recuperation is between one and three degrees, depending on the bending radius, the sheet material and the metallic sheet thickness.

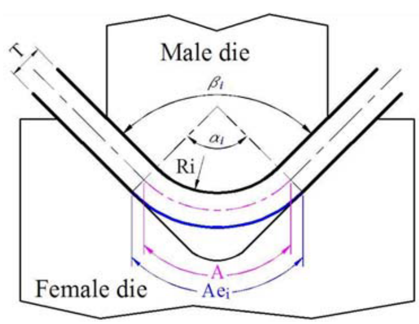

Figure 1: The bending process of metallic sheet (seated)

With this information, it is not possible to design with certainty the bending tools. In this experiment, the problem which needed to be resolved was designing a wood truncated cone (*WTC*) to shape an aluminum sheet truncated cone (*ATC*) of 30° with a minor diameter of 80 mm and a generatrix line of 135 mm.

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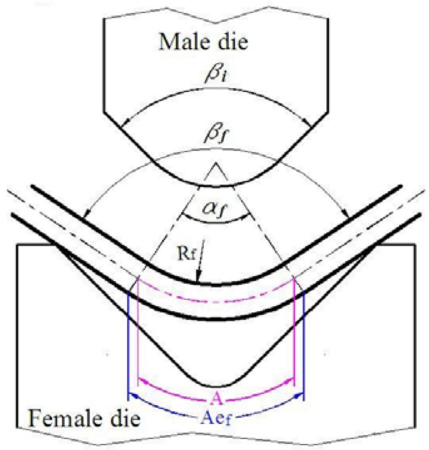


Figure 2: Extracting the male die, and springback of the metallic sheet

Method

Initially, two *WTC* were designed to determine by *trial and error* their minor diameter (*Dm*) allowing us to obtain a *Dm* of 80 mm in the *ATC*. At first, a *Dm* of 70 mm was given to a *WTC* of 30°; the formed cone had a resulting *Dm* of 120.5 mm (Figure 3a). The second *WTC* was given a *Dm* of 60 mm with a calculated conicity of 22°; the shaped cone had a resulting *Dm* of 98.5 mm (Figure 3b). Concluding this phase, the Kalpakjian equation was founded and by taking the obtained experimental results with the first two *WTC*, the equation was applied to determine the *Dm* of the third *WTC* to have a *Dm* of 80 mm in the *ATC*, but the resulting *Dm* for the *WTC* was evidently very small. Therefore, the objective of the second phase was to determine an equation that would better uncover the phenomenon of the elastic recuperation that was evident in the sheet permanent forming process. The stated determined equation (of Damian), was applied to design a definitive *WTC* (see Figure 3c) and the *ATC* was molded. The dimensions of the lateral area of the cone were determined with the respective geometric equations.

Results

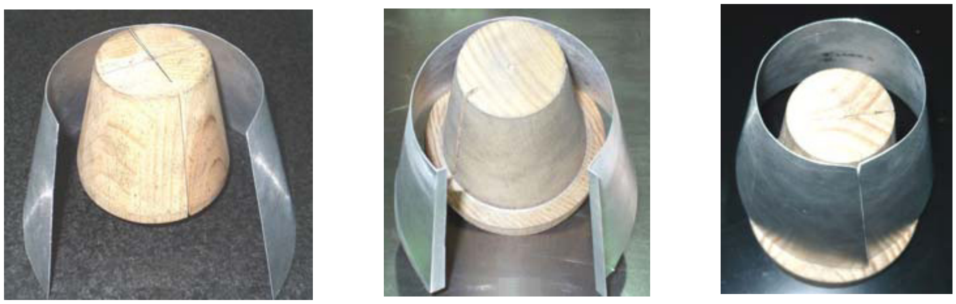
Kalpakjian Equation [5]

This equation was deduced by analyzing the bending process as a pure flexion problem, assuming that for $R_i > 2T$ the neutral axis is located at the center of the sheet thickness and that the applied bending moments generate a plane deformation [6]:

$$\frac{Ri}{Rf} = 1 + 4\left(\frac{RiY}{ET}\right)^3 - 3\left(\frac{RiY}{ET}\right) \tag{1}$$

Where:

R_i — Initial bending radius,



(a) WTC #1: Dm = 70 mm ATC: Dm = 120.5 mm

(b) WTC #2: Dm = 60 mm ATC: Dm = 120.5 mm

(c) WTC #31: Dm = 54 mm ATC: Dm = 81 mm

Figure 3: Aluminum sheet truncated cones molded with wood truncated cones

R_f — Final bending radius,
Y — Yield strength of the material,
E — Young Module of the material,
T — Sheet thickness.

Deduction of Damian's Equation

Figure 1 shows the action of sheet bending with male and female dies in the moment of maximum descent of the male die, but without forcing the compression over both sides of the un-doubled sheet. In Figure 1:

α_i — Initial angle of the bending neutral arc A.
β_i — Initial bending internal angle (angle of the male die).
A — Length of the neutral arc.
Ae_i — Initial length of the most external fiber.

As the male die retracted, the sheet is un-doubled, incrementing the bending radius R and diminishing the angle $\boldsymbol{\alpha}$ and the length Ae of the external arc, given the elastic recuperation of the metallic sheet. Figure 2 shows that:

β_f — Final internal bending angle,
α_f — Final angle of the neutral arc.
R_f — Final bending radius,
Ae_f — Final length of the most external fiber.

That is to say: $\boldsymbol{R}_i < \boldsymbol{R}_f, \boldsymbol{\alpha}_i > \boldsymbol{\alpha}_f, \boldsymbol{Ae}_i > \boldsymbol{Ae}_f, \boldsymbol{\beta}_i < \boldsymbol{\beta}_f$.

The length A of the neutral arc did not vary after the bending process, and its respective position to the internal border depends on the bending radius and bending angle [5]. The following is an approximate equation for its calculation:

$$A = a_i \cdot (R_i + kT) \tag{2}$$

In the ideal case, the neutral axis is located as the center of the sheet thickness, which means, $k = 0.5$:

$$A = a_i \cdot (R_i + 0.5T) \tag{3}$$

In practice however, the value of k varies from 0.33 (for $R_i < 2T$) up to 0.5 (for $R_i > 2T$) [5-6]. The length Ae_i of the arc corresponding to the most external fiber during the sheet bending (see Figure 1) is given as:

$$Ae_i = a_i \cdot (R_i + T) \tag{4}$$

The initial strain ($\boldsymbol{\varepsilon}_i$) of the most external fiber, is the sum of the elastic strain ($\boldsymbol{e}_e$) plus the plastic strain ($\boldsymbol{e}_p$), and is given by the equation:

$$\boldsymbol{\varepsilon}_i = (\boldsymbol{e}_e + \boldsymbol{e}_p) = \frac{Ae_i - A}{A} \tag{5}$$

Substituting (3) and (4) in equation (5):

$$\boldsymbol{\varepsilon}_i = \frac{0.5T}{Ri + 0.5T} \tag{6}$$

This expression is the same as Timoshenko [1]. In Figure 2, the length A of the neutral arc will be given for now as the equation:

$$A = a_f \cdot (R_f + 0.5T) \tag{7}$$

Length (Ae_f) of the corresponding arc of the most external fiber:

$$Ae_f = a_f \cdot (R_f + T) \tag{8}$$

The final strain of the most external fiber ($\boldsymbol{\varepsilon}_f$) will be the plastic deformation ($\boldsymbol{\varepsilon}_p$):

$$\boldsymbol{\varepsilon}_f = \boldsymbol{\varepsilon}_p = \frac{0.5T}{R_f + 0.5T} \tag{9}$$

The difference between the initial and final strain of the most external fiber will be the corresponding strain at the material yield point ($\boldsymbol{\varepsilon}_y$):

$$\boldsymbol{\varepsilon}_y = \boldsymbol{\varepsilon}_i - \boldsymbol{\varepsilon}_f \tag{10}$$

Substituting (6) and (9) in (10) it is shown that:

$$\boldsymbol{\varepsilon}_y = 0.5T \left\{ \left(\frac{1}{R_i + 0.5T} \right) - \left(\frac{1}{R_f + 0.5T} \right) \right\} \tag{11}$$

Applying Damia n's Equation

Substituting in equation (11) the values R_i = 35mm (design value of the first *WTC*) and R_f = 60.25mm (experimental value of the *ATC*) and T = 0.46 mm, (sheet thickness), it is obtained that: $\boldsymbol{\varepsilon}_y$ = 0.0027256.

Likewise, applying equation (11) for the case of the second *WTC* (R_i = 30 mm) and second *ATC* (R_f = 49.25 mm), T = 0.46 mm: $\boldsymbol{\varepsilon}_y$ = 0.00296

Design of the third WTC

Considering that $\boldsymbol{\varepsilon}_y$ = 0.002843 (average value) and given that it is required that R_f = 40 mm:

If Kalpakjian's Equation is applied ($Y/E = \boldsymbol{\varepsilon}_y$):

$$\frac{Ri}{Rf} = 4\left(\varepsilon_y \frac{Ri}{T}\right)^3 - 3\left(\varepsilon_y \frac{Ri}{T}\right) + 1$$

The result is: R_i = 23.24 mm (*Dm* = 46.48mm).

If Damian's Equation is applied: R_i = 26.64 mm (*Dm* = 53.28 mm).

Therefore the third *WTC* was designed with R_i = 27 mm (*Dm* = 54 mm) and we can see the resulting *ATC* in Figure 3 (Its minor diameter is 80 mm).

If Kalpakjian's Equation is applied for R_i = 27 mm, the result is: R_f = 52.1 mm (*Dm* = 104.1 mm), which is experimentally incongruent given that a design value great than R_i (30 mm), obtains an experimental value of R_f less than 52.1 mm (49.25 mm).

Discussion

To resolve the problem of the springback in the forming process of an *ATC* (which is part of a didactic desk lamp), initially the *trial and error method* was utilized in preparing the first two *WTC*. Out of necessity to design a third *WTC* but through applying some equation that would result in its correct design to shape the *ATC* with the design dimensions, Kalpakjian's Equation was utilized, but the results of its application differed from those experimentally observed. Therefore, the strain generated in the moment in which the sheet is bent and the resulting strain after the retraction of the bending force, were analyzed. At that point Damian's Equation was deduced and its application gave more adequate results in determining of the *Dm* of the third *WTC*.

We have considered 30° for the first *WTC* but it was observed that this was erroneously decided, given that in forming the *ATC*, it was observed that the overlap of the lateral edges of the involving area was greater in the minor diameter. The calculus for the second *WTC* was 22° and during the formation of the *ATC*, the overlap of the edges was adequate. Otherwise, the calculus for the third *WTC* was 20° but even though the formed *ATC* had a minor diameter of 80 mm, its mayor diameter was less than 149.9 mm (design value).

From this last result, we conclude that the design degrees of the WTC must be still carefully analyzed taking into account the springback phenomenon when R_i is variable and not only geometrical considerations.

The springback implies just as much a variation in the bending radius as in the bending angle, but in our case the first parameter was more important than the second. We consider as preliminary this first application of Damian's Equation, and we hope that other colleagues will theoretically analyze and also experimentally apply the equation.

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