A NEW TOOL TO ACQUIRE SHEET METAL CYCLIC PLASTICITY DATA FOR HARDENING MODELS

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Abstract

Predictive methods using finite element appear to be the most effective way to identify and solve defects such as springback in sheet metal forming. The accuracy of the predictions depends upon the application of accurate plasticity modelling. A model that is capable to consider the Baushinger effect and cyclic hardening characteristic. This model can be represented by several constitutive equations such as kinematic hardening model, isotropic hardening model or mixed hardening model. Experimental devices and methods are being continuously improved to incorporate increasingly accurate plastic bending characteristics. Part of the task is to improve the methods in acquiring material behaviour. For that a new tool has been developed to test and record the characteristics of sheet metal deformation by investigating the Bauschinger effect factors (BEF) and cyclic hardening behaviour. The developed tool is believed to simulate the actual forming conditions of bending and unbending loading. An initial experimental investigation shows that the tool is capable to record sheet metal behaviour under cyclic loading. The results are analysed for sign of Bauschinger effect and cyclic hardening. It was found that the Bauschinger effect does occur during bending and unbending loadings in sheet metal forming. The BEF value was found to increase as the thickness increases. It was also found that the existence of work hardening stagnation in the cyclic stress-strain curves is not observed. This acquired material characteristic is significant for providing more reliable data in identifying material parameters of the related hardening models. Thus improve the material models as well as the finite element simulation of sheet metal forming.

BEF	Bauschinger effect factor
Y_1, Y_2	Yield stress in forward and reverse cyclic stress-strain curve
F	Force
G	Force from part weight
G_2	Force from part no. 2 (crank)
G_3	Force from part no. 3 (connecting rod)
l	Specimen length subjected to bending (Sheet metal)
α	Sheet metal bending angle
R	Radius of curvature
ρ	Curvature
θ_2	Crank angle
θ_2	Connecting rod angle
X_b	Distance from centre of part no 1 (slider) to rotating centre of part no 2 (crank)
r_2	Part no 2 length (crank length)
r_3	Part no 3 length (connecting rod length)
σ	Stress
$\Delta\sigma_p$	Permanent softening
ε	Strain
M_D, M_U	Downward Moment, Upward Moment
y	Distance of sheet metal layer from neutral axis

1. Introduction

In sheet metal forming, cyclic loading occurs due to bending and unbending of material as in the die draw bead and when the sheet is drawn over a die shoulder corner as shown in Figure 1 (Hosford and Caddell 1993; Sanchez 2010; Yoshida et al. 2002). The bending-unbending deformation causes an effect where the yield stress during reversal loading is lower than the yield stress during forward loading. This effect is known as Bauschinger effect.

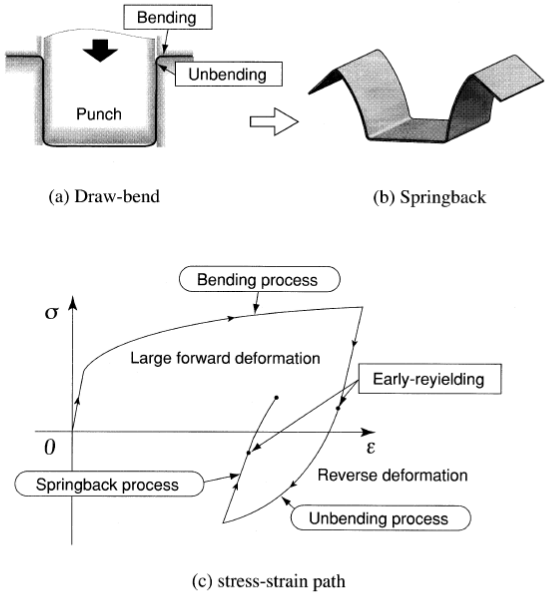

Figure 1 Description of cyclic loading (a) draw-bend (b) springback (c) stress-strain path (Yoshida et al. 2002)

The Bauschinger effect, by definition, is a reduction of yield stress on the reversal of loading when compared to the forward loading. It is also known as early re-yielding. The Bauschinger effect factor, BEF, has been used to quantify the Bauschinger effect according to the following formula:

$$BEF = \frac{Y_1 - |Y_2|}{Y_1}$$

Equation 1

Y_1 and Y_2 are shown in Figure 2. A zero BEF value indicates that no Bauschinger effect is present in loading and unloading deformation (Weinmann et al. 1988).

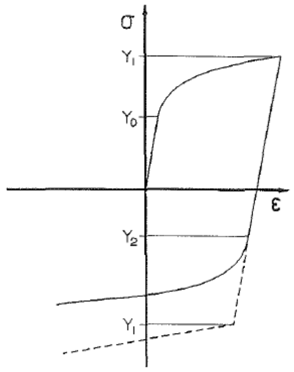

Figure 2 Weinmann's cyclic loading effect (Weinmann et al. 1988)

Yoshida described this cyclic process as having four distinct features: load reversal and Bauschinger point, transient behaviour, work-hardening stagnation and permanent softening as shown in Figure 3 (Yoshida and Uemori 2003).

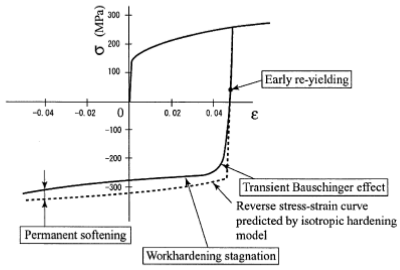

Figure 3 Features of cyclic loading in bending (Yoshida and Uemori 2003)

To improve sheet metal forming simulation, there is a need to incorporate an appropriate constitutive equation capable of describing the Bauschinger effect and so-called cyclic transient derive from near to actual forming process testing tool. This has motivated several researchers to develop bending testers such as (Weinmann et al. 1988), (Yoshida et al. 1998) (Geng et al. 2002) (Zhao and Lee 2002), (Omerspahic et al. 2006), (Carbonniere et al. 2009) and (Boers et al. 2010)

The objectives of this paper is to describe a newly developed bending unbending tool of the sheet metal plasticity with regard to actual cyclic load bending that occurs in the forming process and to evaluate the responsive behaviour of sheet metal materials for any Bauschinger effect, transient behaviour and work-hardening stagnation characteristics. Reliability of the derived data from this tool has been validated. The validation is done by incorporating the material hardening parameters identified from the derived data into the finite element simulation of U bending. The simulation results are compared with the experimental results for any variances.

2. The Cyclic Loading Tool

Figure 4 shows the newly developed bending and unbending testing tool for sheet metal. It is based on the concept of symmetrical crank-slider mechanism, and consists of three main components; slider, cranks, and connecting rods. For the tool to work, the slider is attached to the moving part of the tensile test machine. As the tensile machine is operated, the slider will move downward or upward based on the machine stroke direction. The movement will cause the left and right cranks to rotate and subsequently bend (downward movement) or reverse bend (upward movement) the sheet metal that is being attached to it. By doing this the tool realises a pure sheet bending process.

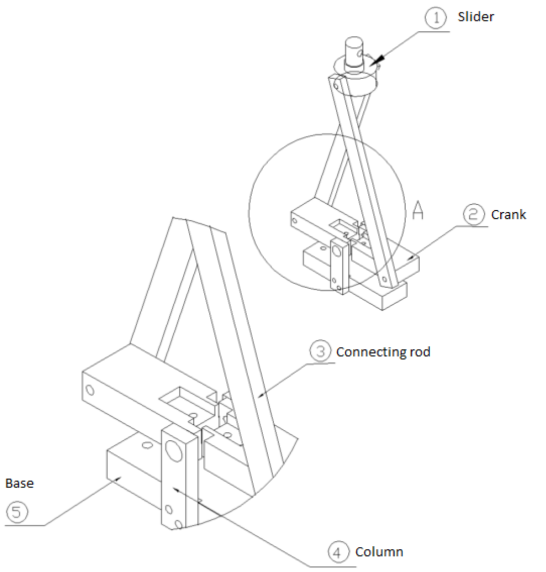

Figure 4 (a) Components of the tool: slider (1), cranks (2) and connecting rod (3) (b) the tool attached to the tensile machine (c) sheet metal in bent position and (d) the produced part after the process.

Figure 5 shows the initial, the bending and the reverse bending position of the tool's crank/holder and the forces acting on it. A detail analysis to configure the bending and reverse bending moment is described in section 2.2. During downward movement, the bending force and the part weight will contribute to the bending moment of sheet metal. During upward movement, the weight of the components however, will resist the reverse bending force. This condition however is believed to have insignificant effect on the real physical of the sheet metal bending. Meaning the Bauchinger effect can still be investigated.

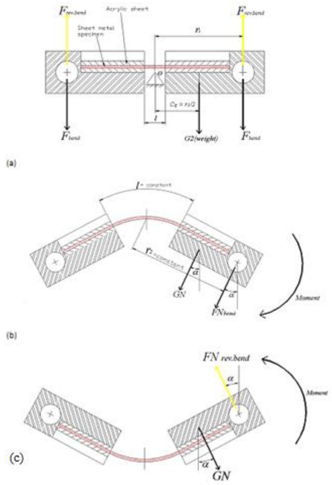

Figure 5 The positions and the forces acting on the crank/holder (a) initial position, (b) bending position and (c) reverse bending position.

The cyclic loading specimen size is 105 mm long and 24.5 mm wide. It is clamped between a pair of acrylic sheets in the tool holders. Figure 6 (a) shows the specimen together with 2 pairs of acrylic sheets used to minimise friction during the bending and unbending processes. Sheet metal plates are placed on the top of the acrylic sheets to prevent them from being tilted during the bending and unbending processes. Figure 6 (b) and (c) show the finishing product and the bending process.

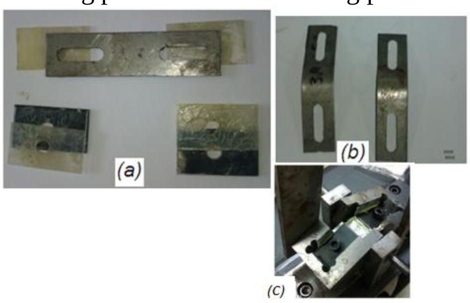

Figure 6 (a) Acrylic sheets used to minimise friction effect during bending and unbending processes (b) parts after bending and unbending processes (c) bending process

Fasterners are used to clamp the sheet metal plates, the acrylic sheets and the sheet metal specimen. The fasterners are manually tightened to give a light compression force so as to allow the sheet metal specimen to slide between the acrylic sheets during the bending and unbending processes. To avoid axial stretching due to restriction from the fastener, oblong shape holes are cut on the specimen. These holes indirectly also reduce the contact area between the test specimen and the acrylic sheets and subsequently minimising the friction effect. Lubrication, 1200-2 from Lubriplate, is applied to further reduce friction effect.

2.1. Curvature and Strain

It is necessary to convert the acquired raw data in the form of displacement into curvature and then into bending strain. Thus, the tool and the specimen geometrical relationship during bending condition are analysed. Figure 7 shows the relationship between the tool angles (θ_2) and the sheet metal bending angle (α), to be related to curvature (ρ) by an equation, ρ=1/radius of curvature (R).

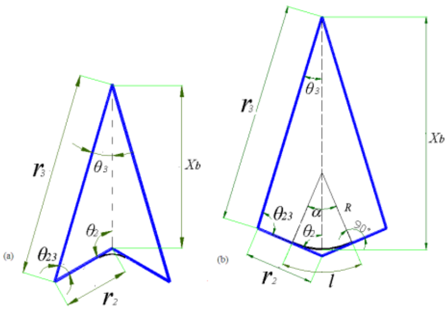

Figure 7 Geometrical parameters of the tool and sheet metal specimen (a) bending direction and (b) reverse bending direction

The symbol l and α are the length of sheet metal that is being subjected to reverse bending operation and its bending angle. The length is equal to the gap between the rights and left tool holder or the cranks. The bending angle, α depends directly on the crank angle, θ_2 and indirectly to the connecting rod angle θ_3. The first angle is a function of the slider displacement in the form of X_b distance and the tool length, r_2 and r_3 whilst the connecting rod angle is a function of the crank angle and the tool length. The relationship is described by Equation 2 and 3 (Shigley and Uicker 1995).

$$\theta_2 = \cos^{-1}\frac{X_b{}^2 + r_2{}^2 - r_3{}^2}{2X_b r_2}$$

Equation 2

$$\theta_3 = Sin^{-1}\left[\frac{r_2 Sin\,\theta_2}{r_3}\right]$$

Equation 3

θ_2 = *crank angle*

θ_3 = *connecting rod angle*

X_b = distance from centre of slider to rotating centre of crank

r_2 = *crank* length

r_3 = *connecting rod* length

The curvature of sheet metal bending is calculated using Equation 4 (Marciniak et al. 2002).

$$\rho = 1/R$$

Equation 4

The following procedure and Figure 8 show how the curvature is being derived based on the tool's geometrical configuration. The crank angle in a downward movement is always in the range of 90 < θ_2 <180. To calculate curvature, triangle $\angle ABC$ is used to find relationship between the crank angle and the bending angle and is described by Equation 5.

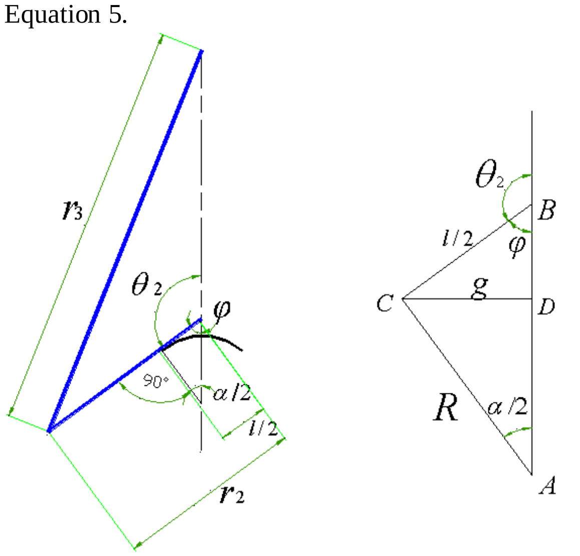

Figure 8 Tool's geometrical configuration for curvature derivation during downward movement/bending operation

$$\frac{\alpha}{2} = 180 - 90 - \varphi$$

$$\varphi = 180 - \theta_2$$

$$\frac{\alpha}{2} = \theta_2 - 90$$

Equation 5

Since $90 < \theta_2 < 180$, so $\alpha/2$ is always positive. Based on Equation 4 and 5 (Marciniak et al. 2002), the curvature formula, Equation 6, is derived using angles in radian. This derivation is shown for clarification.

$$l = R\alpha$$

$$R = l / \alpha \ or$$

$$R = \frac{l/2}{\alpha/2}$$

$$R = \frac{l/2}{\theta_2 - 90}$$

$$\rho = \frac{1}{R}$$

$$\rho = \frac{\theta_2 - 90}{l/2}$$

Equation 6

Derivation result for upward movement (reverse bending) is described by Equation 7.

$$\frac{\alpha}{2} = -(\theta_2 - 90)$$

Equation 7

To change the curvature value into strain the following formula is used (Marciniak et al. 2002):

$$\varepsilon = \ln[1 + y\rho]$$

Equation 8

where *y* is a distance from the middle surface of the sheet metal. For y equal to half of the sheet metal thickness, the strain calculated is for the outer surface.

2.2 Moment and Stress

To derived equations for bending moment, the crank-slider static force analysis is performed with an assumption that the inertial force could be neglected due to a nearly constant or uniform motion so the value of such force is relatively small compared to other forces such as gravity force and reaction forces from the sheet metal specimen. Friction forces are assumed to be negligible. An analysis to derive the moment equation is performed based on a downward movement and an upward movement of the slider. For downward movement (bending operation), the analysis began by configuring reaction forces acting on the tool and its components by using free body diagram as shown in Figure 9.

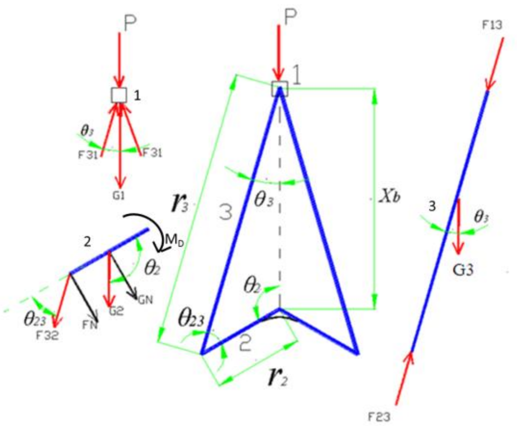

Figure 9 Free body diagrams for a downward movement of the bending tool and its components

Based on the free body diagram and an analysis of sum of forces and sum of momentums equations, Equation 9 and 10 for downward and upward moments are derived.

$$M_D = \frac{r_2}{2}\left[(P + G_1 + 2G_3)\frac{\sin(\theta_2 + \theta_3)}{\cos\theta_3} + G_2 \sin\theta_2\right]$$

Equation 9

$$M_U = \frac{r_2}{2}\left[(-P + G_1 + 2G_3)\frac{\sin(\theta_2 + \theta_3)}{\cos\theta_3} + G_2 \sin\theta_2\right]$$

Equation 10

The bending moment, M can be converted into stress using Equation 11 (Marciniak et al. 2002).

$$M = \int_{t/2}^{t/2} \sigma W \, y \, dy$$

$$\sigma = \frac{4M}{Wt^2}$$

Equation 11

W and t are the width and thickness of the material.

3. Results and Discussions

A few experiments were performed with bending angles between 20 degree (first bending) to 40 degree (subsequent bending) for 1.5 mm and 2 mm thick low carbon steels. Results in the form of stress versus strain graphs are shown in Figure 10 and Figure 11.

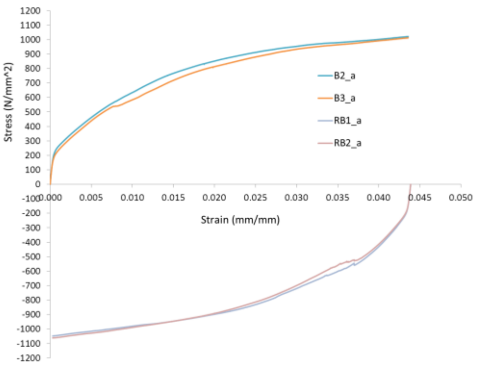

Figure 10 Cyclic stress-strain graphs for low carbon steel 2 mm thick

Table.1. The values for Y_1 are taken from average of B2 and B3 cyclic data and Y_2 are taken from average of RB1 and RB2 cyclic data.

The values in the tables prove that the Baushinger effect exists when sheet metal is subjected to bending and unbending loadings. It is very interesting to note that the thickness of the material seemed to have influence on the Bauschinger effect

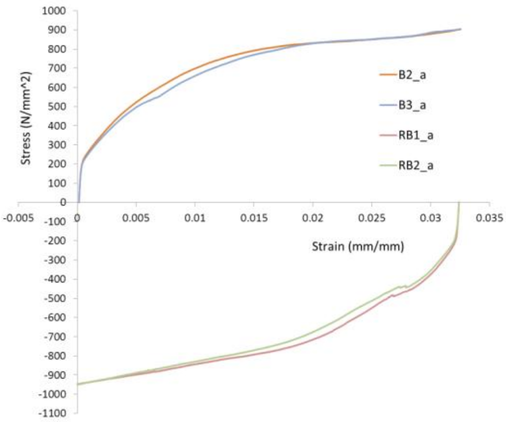

Figure 11 Cyclic stress-strain graphs for low carbon steel 1.5 mm

From the graphs, the bending and reverse bending show a distinct elastic behaviour before the yield point. The cyclic loading reaches a steady state condition or stabilized immediately after the first cycle. The curves show a nonlinear stress-strain relationship after the yield point. A smooth elastic-plastic transient curve is followed by rapid work-hardening curve. Work hardening stagnation as mentioned by Yoshida and Uemori (2003), however, is not visible. From the onset of plastic region to near the middle of the plastic region the hardening curves for each specimen seem to be consistent in path. The curves however are slightly deviated from each other towards the end of the plastic region. This deviation is believed to be caused by friction between specimen's and the tool holders' surfaces. The reverse re-yielding from the results of the current work is quite obvious to trace and there is a distinct indicator for the particular point. This lead to a simple 0.002 offset way in identifying the reversal yield stress point useful for calculating Baushinger Effect Factors (BEF) by using Equation 1. The results are shown in

as indicated by the increase of BEF values when the thickness increased. This is contrary to the finding by Weinmann who stated that the material thickness had insignificant relationship with the Bauschinger effect. This finding however should not over rule Weinmann's statement completely as the materials used for experiments may undergo different rolling processes during production. Further investigation is necessary for validation.

Table.1 Summary of BEF data for cold rolled low carbon steel

2 mm thick							
no	Y_1-B2	Y_1-B3	Average	|Y_2-RB1|	|Y_2-RB2|	Average	BEF
1	987.971	990.637	989.304	144.414	138.192	141.303	0.857
2	1061.245	1029.037	1045.141	178.515	178.515	178.515	0.829
3	1014.546	1017.451	1015.998	191.017	186.420	188.719	0.814
						Average	0.834

1.5 mm thick							
no	Y_1-B2	Y_1-B3	Average	|Y_2-RB1|	|Y_2-RB2|	Average	BEF
1	937.421	938.102	937.762	168.923	161.782	165.353	0.824
2	936.890	922.366	929.628	165.516	173.485	169.501	0.818
3	837.108	846.571	841.839	203.075	202.641	202.858	0.759
						Average	0.800

4. Conclusions

The following conclusions are derived based on the experimental results conducted from the newly developed tool.

i. The developed experimental tool is capable of providing significant data for analysis of the Bauschinger effect and understanding behaviour of sheet metal materials undergoing cyclic loading.
ii. The existence of work hardening stagnation in the cyclic stress-strain curves is not observed. This likely due to small bending angle of about 20 degree (first bending) to 40 degree (subsequent bending) which produced insufficient accumulated strain for work hardening stagnation to be observed.
iii. The Bauschinger effect does occur during bending unbending loading in sheet metal forming as indicated by BEF values in Tables 1. Thus the Bauschinger effect should be considered in finite element simulation of sheet metal forming through the use of kinematic or mixed hardening model.

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