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Research Paper

SPRING-BACK IN MULTI-POINT DISCRETE DIE V-BENDING

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Sheet metal forming using Multi-Point Discrete Dies (MPDD) is a forming technique in which the punch and die surfaces are discretized using arrays of pins leading to manufacturing flexibility and the ability to produce more than one product with the same die. The present paper considers the spring-back problem of the V-bending process using a Multi-Point Discrete Die. An experimentally validated ABAQUS finite element simulation model is developed in the present study to predict the punch load-displacement, bending angle, and the springback factor. For the same material and thickness, larger pin size is found to reduce springback factor but with a tendency for dimples occurrence. For the same thickness and pin side length, the use of polyurethane elastic cushion (interpolator) is found to eliminate the dimples occurrence, but causes a deviation in the bending angle. Generally, the study suggests that using the elastic cushion, decreasing the pin size, and adding controlled over stroke coining enhance the conditions for obtaining accurate final V-bend angle.

Keywords: Multi-point discrete dies, V-bending process, Sheet metal forming, Finite element method

INTRODUCTION

Conventional stamping is one of the most common sheet metal forming methods which involves the use of a matched solid die set, and its main advantages are the short production time and high productivity. However, large initial investments and long setup time make conventional stamping processes inflexible and only profitable for mass production. In some cases such as in aerospace and ship building industries there is always a need to develop tools to produce small quantities of several parts (Walczyk D F, 1996). Using conventional dies under such conditions is highly expensive. Sheet metal forming using Multi-Point Discrete Dies (MPDD) technique in which the punch and die surfaces are discretized using arrays of pins

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is a flexible manufacturing method (Hardt D E *et al*., 1982) which is developed for economic batch production and rapid prototyping of sheet metal parts along with other forming processes such as rubber pad forming (Peng L *et al*., 2009), incremental forming (Kim T and Yang D, 2000) and laser forming (Shen H and Vollertsen F, 2009).

However, as in other sheet metal forming methods, spring-back is an inevitable phenomenon in MPDD processes. Regarding the fact that in MPDD the geometry of forming tool is simply adjustable without any additional cost, the die surface can be modified frequently to adopt desired workpiece geometry after springback. Many studies in this area have focused on compensation of spring-back in accuracy. Hardt *et al*. (1982) employed a reconfigurable discrete die with a closed-loop shape control system to predict the optimum surface of the die, while compensating for both elastic properties of rubber interpolator and machine errors. Zhang *et al*. (2006 and 2007) employed inverse displacement method to optimize the die surface in multi-point sandwich forming. Based on finite elements (FE) simulation results and through an iterative trend, Liu *et al.* (2010) managed to compensate the dimensional error caused by non-uniform deformation of elastic cushion as well as the springback in multi-point stretch forming. Li *et al*. (2010) considered flexibility advantage of MPDD and introduced multi-step MPDD as an efficient method to reduce the springback. In this way, the forming process is supplemented in several stages. The multi-stage forming provides a uniform stress distribution in formed parts which has a significant impact on cutting down the springback. In order to minimize the shape deviation in thick plates used in shipyards, Hwang *et al.* (2010) proposed a new method in which the integration of iterative closest point algorithm, displacement adjustment method and FE simulation are forming the sides of automatic springback compensation triangle.

The present work investigates some major parameters that would affect springback in V-bending using MPDD. This process is elected since it represents a bench-mark problem where results can readily be compared with conventional V-bending process.

EXPERIMENTAL WORK

In this study, experimental work is carried out to determine the necessary material parameters and facilitate the validation of the finite element model as detailed in (Abusrea M R, 2014).

Materials: Two materials, aluminum and low carbon steel (in the annealed state) are

Table 1: Mechanical Properties Obtained for Annealed Aluminum and Steel

	Young's Modulus, E (GPa)	Poisson's Ratio, v	Yield Stress, σ_y (MPa)	Ultimate Stress, σ_u (MPa)	Strength coefficient, K (MPa)	Strain-Hardening, n	Density, ρ (kg/cm^3)
Aluminum	70	0.33	44	65	127	0.2028	2.7
Steel	202	0.3	242	317	554	0.213	7.84

considered in the present finite element numerical investigations. These materials are assumed to be isotropic and homogeneous, with the mechanical properties given in Table 1.

A Polyurethane interpolator or elastic cushion is adopted. The elastic cushion behaves in a non-linear hyperleastic manner and can be generally assumed to be virtually incompressible. The Ogden model (N=3) [12] is used to represent the constitutive relation of the cushion. The Ogden strain energy potential U [12] is defined in the terms of the principle stretches λ1, λ2, and λ3:

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_1} + \bar{\lambda}_1^{\alpha_2} + \bar{\lambda}_1^{\alpha_3} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}\left(J -\right)$$

Construction of the MPDD for V-bending

Figure 1 shows the MPDD designed and used in the validation of the present finite element simulation model as detailed in (Abusrea M R, 2014). Die assembly is installed on the compression side of a WDW-100D microcomputer controlled universal testing machine having a capacity of 100 kN. The multi-point discrete die (MPDD) construction consists of three side plates and the fourth is a clamping plate, two guide rods to guide the punch movements, and a matrix of 7x15, 5mm side length square pins. A specially designed positioners for the male and female parts are used to obtain a 90^o V-bends (Abusrea M R, 2014). In V-bending, the positioning is done based on a straight line (V-bend legs) which acts as a tangent over the pins. The relationship the relative height between two adjacent pins (Δh) can be written as follow:

Δh = W.tar, where θ is the bending angle and W is the pin side length (Figure 2).

Finite Element Modeling for the V-Bending process Using MPDD

Finite element simulations for MPDD V-die bending are carried out using ABAQUS/ Explicit and ABAQUS/Standard modules. The loading stage is simulated using ABAQUS/ Explicit module while the unloading stage and spring-back calculations are carried out using ABAQUS/Standard (Osman M A, 2009 and Osman M A *et al*., 2010). Punch and die are modeled as discrete rigid parts and plane strain condition is assumed. The material model uses isotropic linear elastic-work hardening material with properties determined as per the tensile tests experiments. The friction coefficient between the sheet and the tooling surfaces was initially adjusted in such a way that the load-displacement and spring-back measurements obtained from the finite element simulations agreed with those obtained experimentally (Abusrea M R, 2014). Values of springback factors are obtained by comparing the angles in the fully loaded state in ABAQUS/Explicit and that for complete unloaded state in ABAQUS/Standard. In order to calculate these angles, nodes distributed along the loaded and unloaded sheet surface are assigned and the slopes of the straight lines for both sides are obtained from fitting a

Table 2: The Material Parameters of Polyurethane Cushion, Liu *et al*. [13]

	μ_1	α_1	μ_2	α_2	μ_3	α_3
Polyurethane	–475.63	1.285	203.851	2.312	281.391	0.108

Figure 1: MPDD Assembly and the Positioners Used in the Present Work

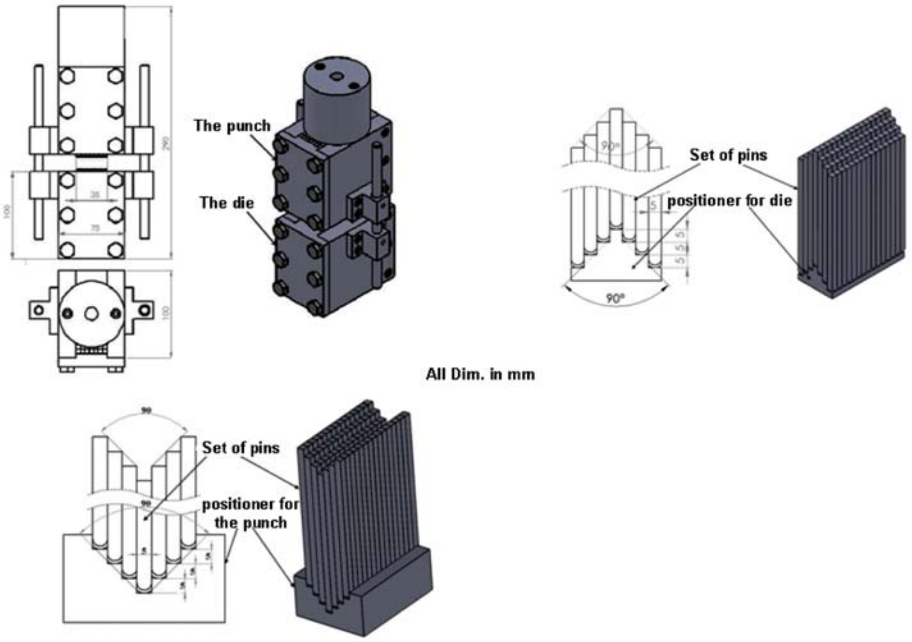
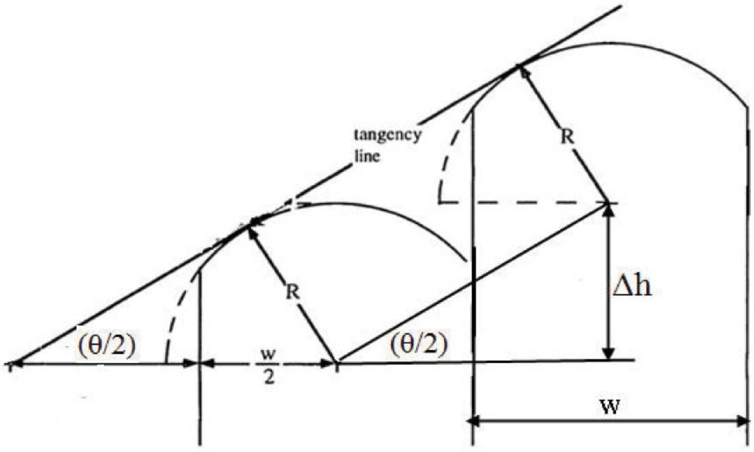


Figure 2: Calculations for Pin Positioning for V-bending Process



straight line along the points assigned and the bending angle is defined as the summation of these two sides angles

In the present study, three pin side lengths of 1, 2, and 5 mm are considered with pin tip radii of 0.71, 1.41, and 3.54 mm respectively.

RESULTS AND DISCUSSION

Figures 3 and 4 show the effect of thickness and pin tip radius on the springback factors of steel and Aluminum specimens. It can be observed that for all pin radii, as the thickness increases the springback factor increases. On

Figure 3: Effect of Thickness on the Springback Factor for MPDD V-bending of Steel and Al

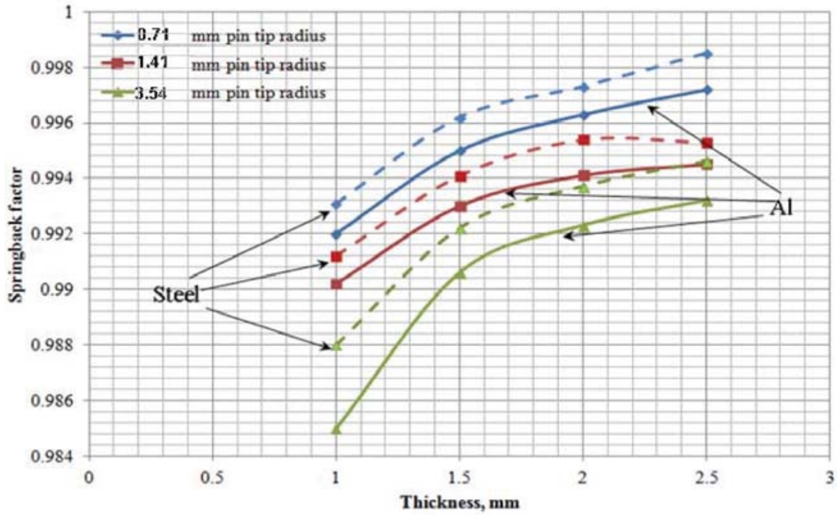
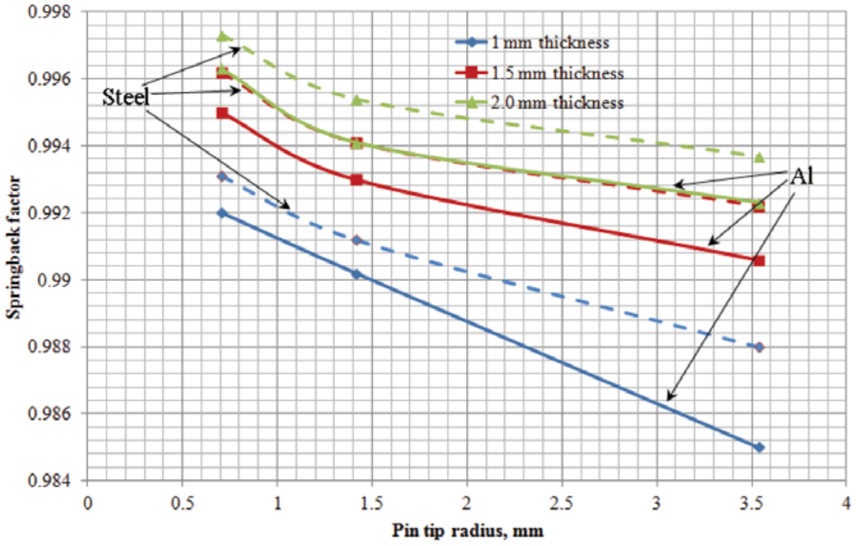


Figure 4: Effect of Pin tip Radius on the Springback Factor for MPDD V-bending of Steel and Al



the other hand, the springback factor decreased as the pin tip radius increases.

Effect of over-stroke on MPDD v-bending without interpolator. Unlike the conventional V-bending process, the final V-bend quality using MPDD is highly dependent on the amount of over-stroke which impose a coining force on the V-bend. Figure 5 shows how the nominal stroke for V-bending process is calculated. Any amount of over-stroke could lead to the appearance of dimples which is a major problem in MPDD sheet metal forming. Dimples represent unacceptable distortions in the produced surface and localized thinning in the sheet. To study this phenomenon, small increases of 1% and 2% are added to the nominal punch stroke to study the effect of over-stroke on the final V-bend quality.

Figure 6 shows the deformed shapes and effective plastic strains for 1 and 2 mm thickness Aluminum specimens with 2% over-stroke. Dimples appear clearly at both sides of the V-bend due to over stroke. Here, the measurements of dimples are taken as the %thinning for different positions on the V-bend legs at the end of loading stage. These positions represent the contact points between the pins of both the punch and the die with the workpiece. Figure 7 shows the %thinning versus position for 1.5 thick aluminum

Figure 5: Calculation of Nominal Stroke for V-bending Process

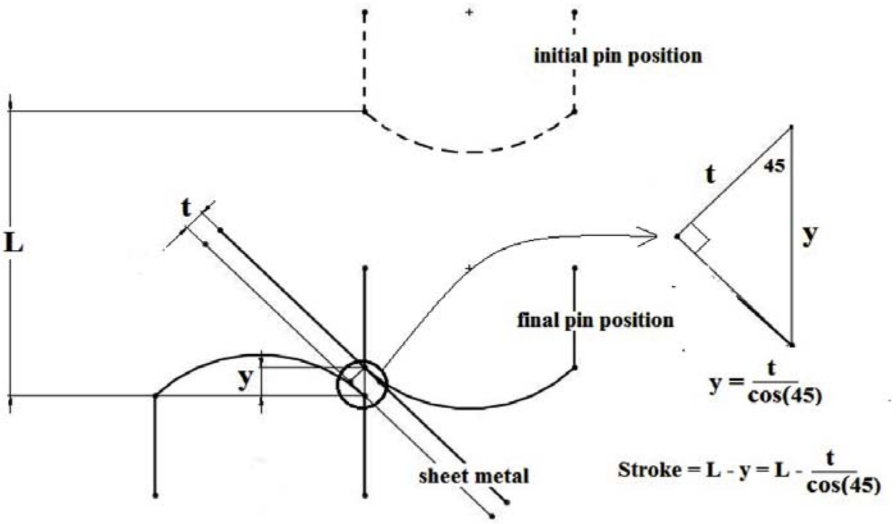
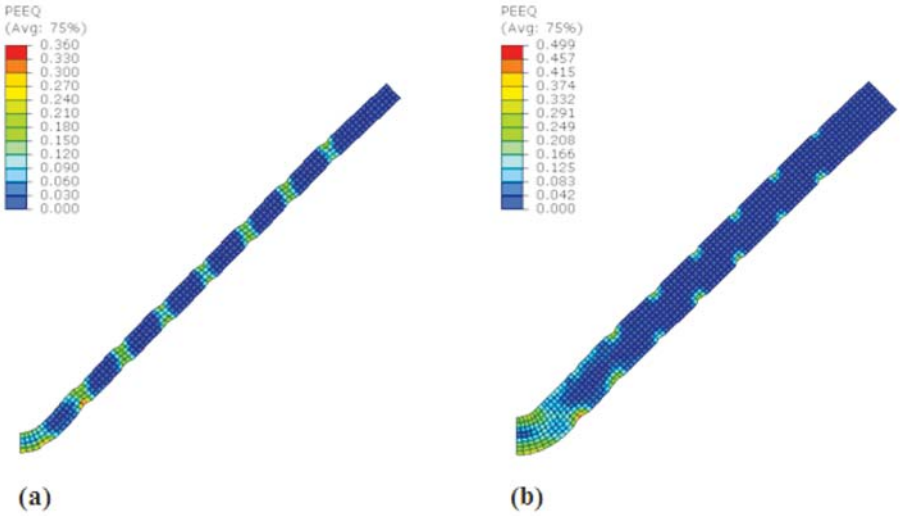
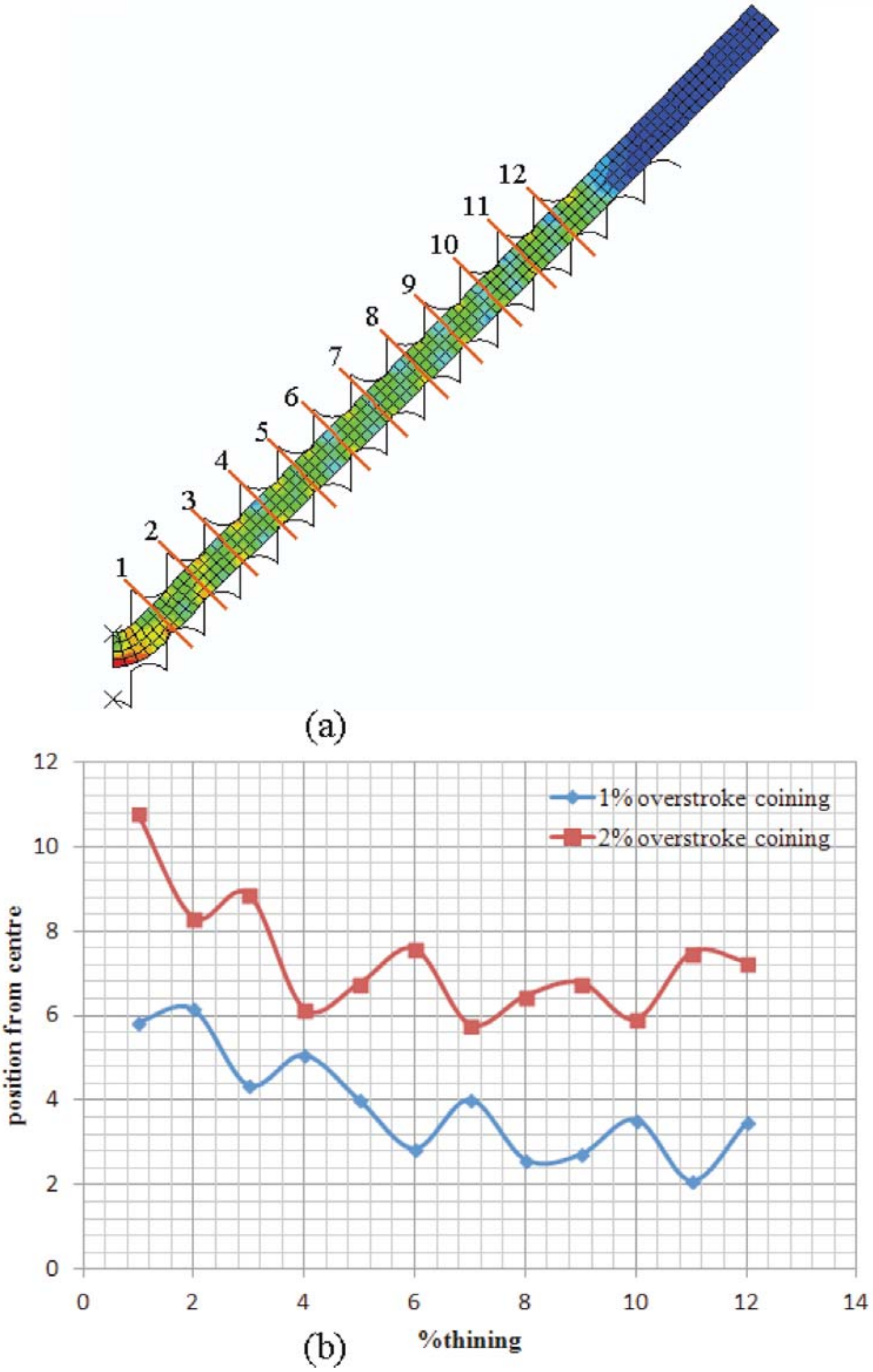


Figure 6: Deformed Shape with Plastic Equivalent Strain, PEEQ, Distribution in MPDD V-bending of Aluminum Using 1.41 mm pin tip Radius (a) 1 mm Thick and (b) 2 mm Thick



(a) (b)

**Figure 7: (a) Locations thinning measurement point,
(b) Percentage thinning at positions in
(a) for V-bending of 1.5 mm thick Aluminum specimen and 0.71 mm pin tip radius**



specimen and 1mm pin side length (0.71 mm pin tip radius). Figures 8 and 9 show comparisons of the spring-back factors obtained with nominal strokes and with slight over-strokes. Apparently, the slight over stroke improves the spring back factor.

Effect of elastic cushion (Interpolator) on MPDD V-bending. One of the known solutions for the dimples problem is the integration of an elastic cushion (Interpolator) between the specimen and the die surfaces. Zhang *et al.* (2008) used single elastic cushion between the sheet metal and the lower half only because the upper half of the die was made of polyurethane pad instead of discrete pins. Liu *et al*. (2012) used elastic cushion from both sides. This type of structure is called sandwich structure and is considered in the present work. Olsen (1980) stated that the use of upper half made of hyper-elastic material (i.e Polyurethane) instead of a matrix of pins may lead to higher dimpling problem. In the FE model for this structure pair of hyper-elastic polyurethane elastic cushion sheets are inserted between the workpiece and the punch and die surfaces.

Figures 10 and 11 compare the springback factors for MPDD V-bending of Aluminum with and without using the elastic cushion for two different pin sizes. It is shown that for all pin sizes the springback factor for the case without elastic cushion is higher than for those with the elastic cushion. Figures 12 and 13 show the deformed shapes, equivalent stress and plastic strain for V-bending of 2 mm thick Al with and without using elastic cushion. Apparently, the higher plastic strains obtained in the case of v-bending without cushion improves the spring-back factor. The use of elastic cushion causes a large bend radius,

Figure 8: Comparison of Springback for MPDD V-bending of Aluminum using 3.54 mm pin tip Radius

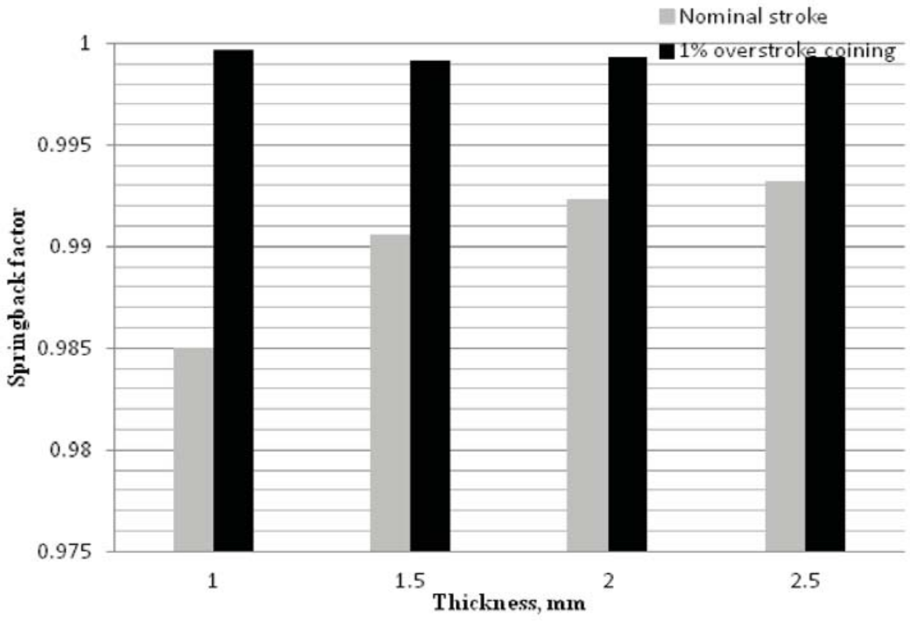


Figure 9: Comparison of Springback for MPDD V-bending of Steel Using 3.54 mm pin tip Radius

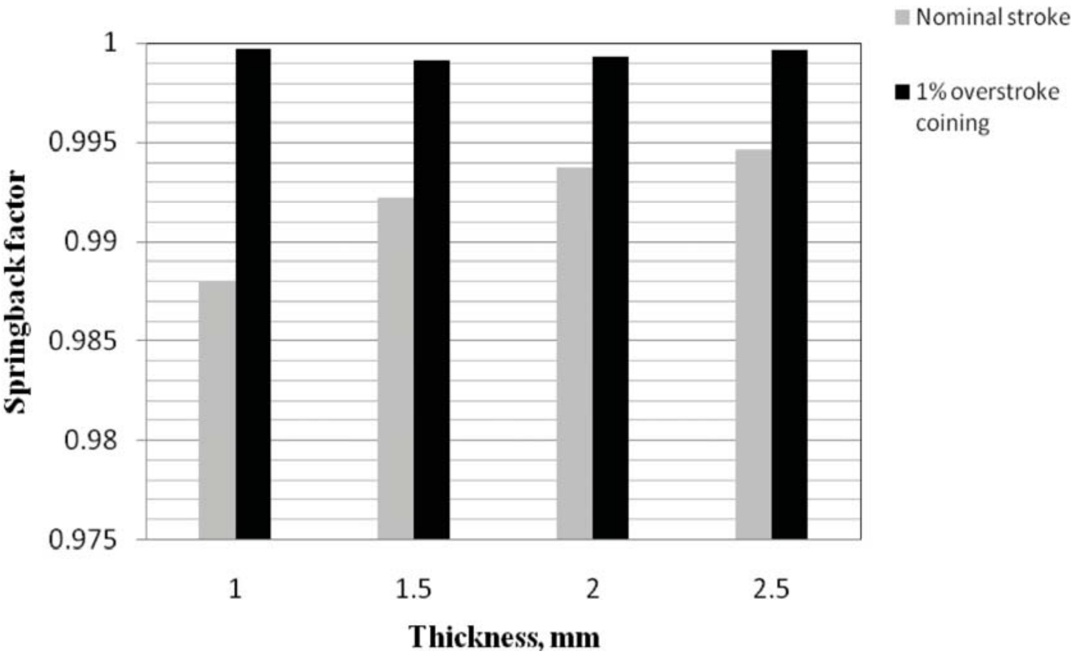


Figure 10: Effect of Thickness and Using Elastic Cushion for V-bending of Aluminum and 0.71 mm pin tip Radius

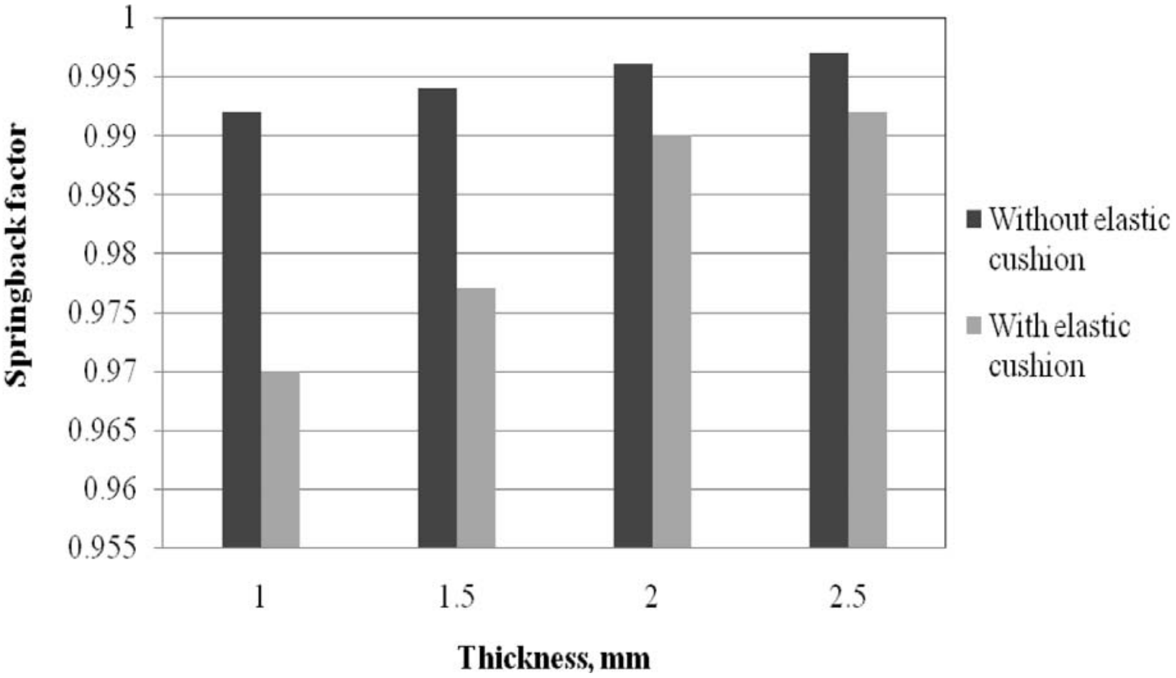


Figure 11: Effect of Thickness and Using Elastic Cushion for V-bending of Aluminum and 1 mm pin Size

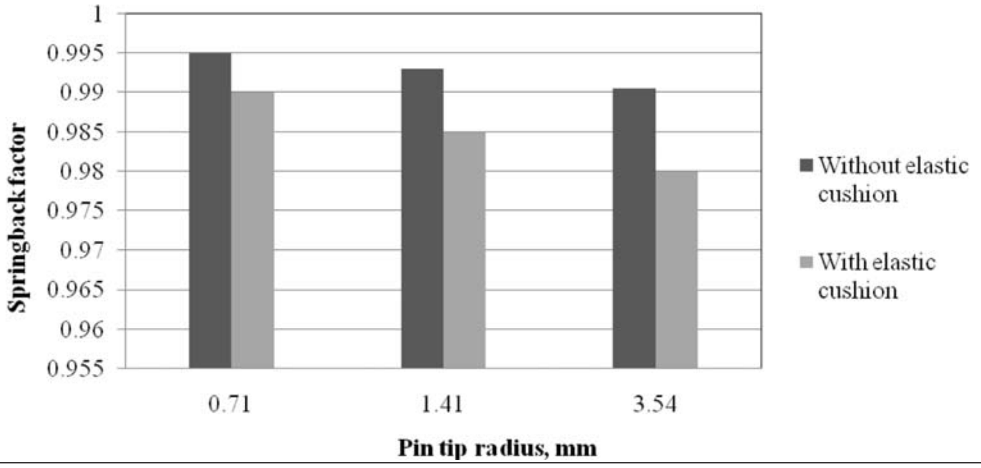


Figure 12: Deformed Shape for MPDD V-bending with Elastic Cushion for 2 mm Al Using 1.42 mm pin tip Radius (a) Equivalent Stress S, and (b) Plastic Equivalent Strain PEEQ

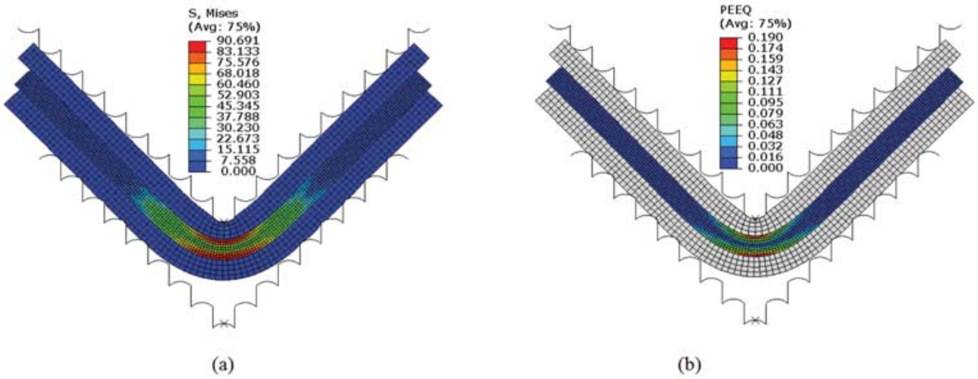
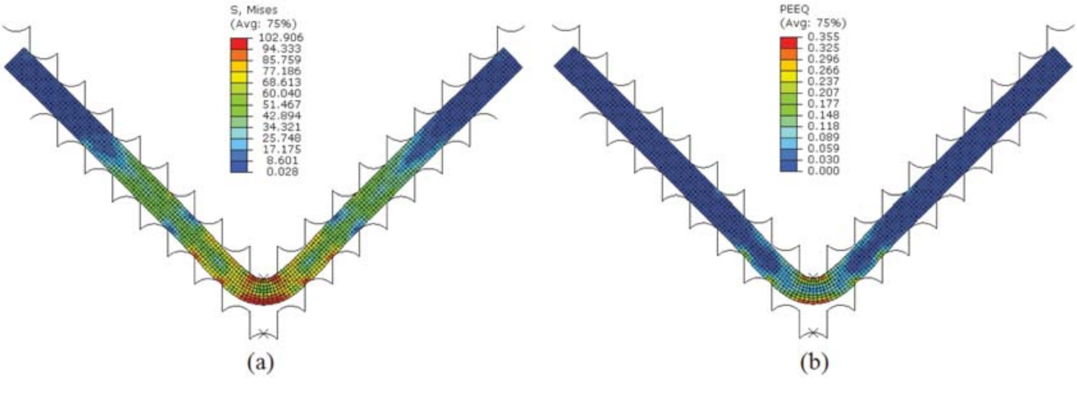


Figure 13: Deformed Shape for MPDD V-bending Without Elastic Cushion for 2 mm Al Using 1.42 mm pin tip Radius (a) Equivalent Stress S, and (b) Plastic Equivalent Strain PEEQ



and this could lead to smaller spring back ratios as discussed by Osman *et al*. (2010).

Figure 14 shows the deformed shape with plastic equivalent strain (PEEQ) distribution of the sandwich MPDD V-bending process for 1mm Aluminum with 5% over stroke. It can be shown in this figure there are no dimples even if for 5% over stroke. In addition, Figure 15 shows the effect of over stroke on the bending angle for loading stage for the sandwich MPDD V-bending for 1 mm Aluminum with 1% to 5% over stroke, it can be concluded that the application of a moderate over stroke may enhance the bending angle for loading stage. The punch travel to achieve the desired final shape with least risk of failures is considered optimum stroke Cai Z and Li M, 2002).

Figure 14: Effect of over-stroke on the Deformed Shape with PEEQ Distribution for Sandwich MPDD V-bending of 1mm Aluminum and 2mm pin Size, 5% Over-stroke

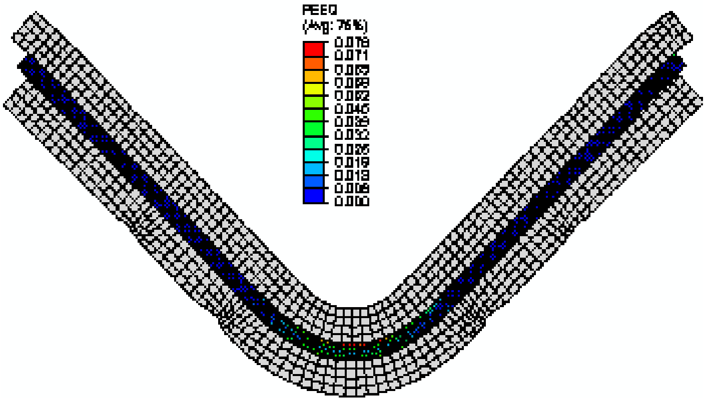
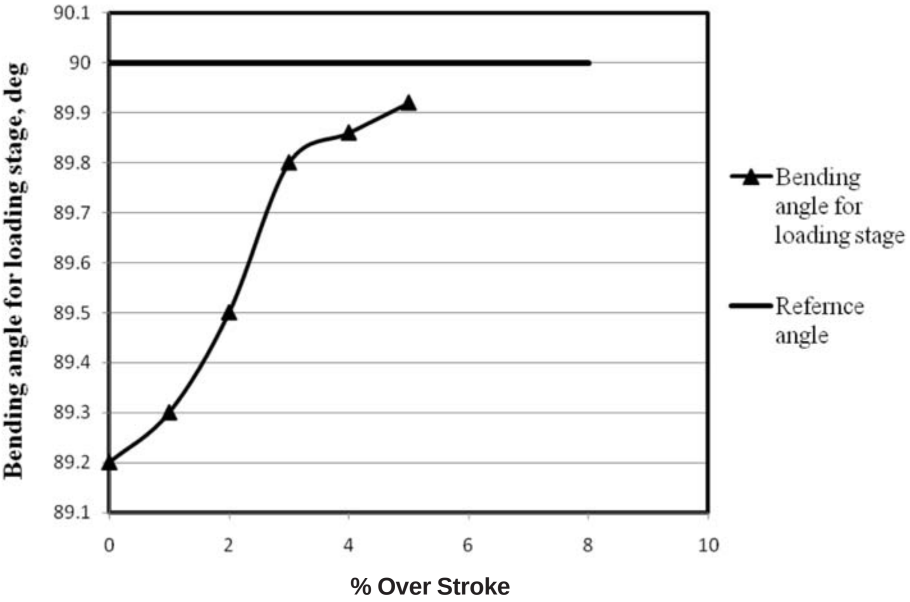


Figure 15: Effect of over-stroke on the Bending Angle for Loading stage for sandwich MPDD V-bending of 1mm Aluminum and 2mm pin Size



CONCLUDING REMARKS

Finite element analyses have indicated that any small amount of over stroke coining could cause the appearance of dimples. The results have shown that as the pin size decreases the number and amount of dimples increases. The dimpling occurrence have been successfully eliminated by using an elastic polyurethane cushion (Interpolator) in a sandwich MPDD V-bending. However, the use of elastic cushion (interpolator) have led to a reduction in the springback factor and a decrease in the accuracy of the final bending angle prediction. The over-stroke or coining is not necessarily needed in the MPDD V-bending without elastic cushion with correct pin positioning. However, a slight over-stroke has been found to enhance the conditions for obtaining accurate V-bending angle when using elastic cushion. Generally, the study suggests that using the elastic cushion, decreasing the pin size, and adding controlled over stroke coining enhance the conditions for obtaining accurate final V-bend angle.

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