Experimentation and Numerical Modeling of Forging Induced Bending (FIB) Process

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Abstract. Accurate prediction of the final shape using numerical modeling has been a top priority in the field of sheet and bulk forming. Better shape prediction is the result of a better estimation of the physical stress and strain state. For experimental and numerical investigations of such estimations, simple benchmark processes are used. In this paper a benchmark process involving forging (flattening) of sheet metal between punch and die with negative clearance is proposed. The introduced material flow results in bending. Easy measurability of the angle of this bend makes this process suitable for validation purpose. Physical experiments are performed to characterize this bending angle due to flattening. Furthermore a numerical model is developed to capture this phenomenon. The main focus of this paper is the validation of the numerical model in terms of accurate prediction of the physical results.

INTRODUCTION

Prediction and validation of experimental results with numerical models have always been a focus since the advent of computational sciences. Each new numerical modeling technique is aimed to accurately predict the results of a characterization experiment. At industrial level of application this boils down to accurate prediction of the final part geometry and associated stress-strain state using numerical simulations. Generally the shape of the part is dependent on the distribution of the stress and strain in the part. Accurate modeling of the stress-strain distribution will lead to a better shape prediction. Likewise better shape prediction by a model of a physical test means that the stress-strain distribution is probably in accordance with the stress-strain distribution in the physical part.

The geometry of industrial products generally tends to be complex. An efficient way to investigate an industrial process is to design a benchmark process which involves similar deformations and at the same time is simple in terms of measurability. This benchmark is then simulated using state of the art modeling techniques and compared with the physical results in terms of final geometry. In this work a new benchmark (explained in the next section) involving bulk forming process of sheet metal [1] is suggested. An overview of bulk forming process of sheet metals can be found in [1] and [2]. Similar processes are also investigated using thin micro dimensioned sheets such as in [3] and [4]. The benchmark discussed here will involve bulk forming of metal sheets in micro dimensions. The goal is to efficiently model this benchmark process to predict the shape of the physical test results. Both numerical and physical parameters of the model will be considered for developing the simulation model.

FORGING INDUCED BENDING, A BENCHMARK

A benchmark process involving forging (flattening) of the sheet metal is proposed as illustrated in Fig. 1. In this process sheet of chromium based stainless steel (CS) received in ferritic form with thickness in range of 200 μm is pressed between a die and punch with negative clearance. As a result of such forging the free end (flap) is bent at an angle. The angle depends on the deformation produced in the forged area. The ease in angle measurement makes this benchmark suitable for validation of shape prediction. The angle results can be used to improve the shape prediction of the numerical model with respect to the measured angle results of a physical model.

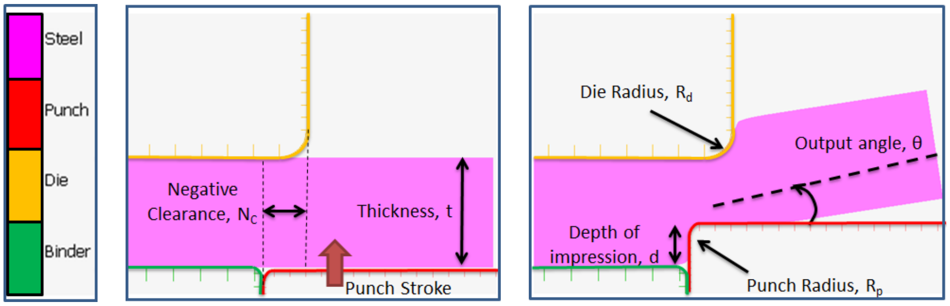


FIGURE 1: Illustration of the forging induced bending (FIB) process: (*left)* start of process and *(right)* process at deepest point.

PHYSICAL EXPERIMENTS

Physical test were performed for the FIB process using a general purpose press with specially designed punch and die tools. The specifications of the process are listed in Table 1. After forming the samples, geometrical features such as depth of impression d and output angle θ are measured with an optical microscope Fig. 2 (a). The results of the angle with respect to the normalized depth $ND=d/t$ are shown in Fig. 2 (b).

NUMERICAL MODEL

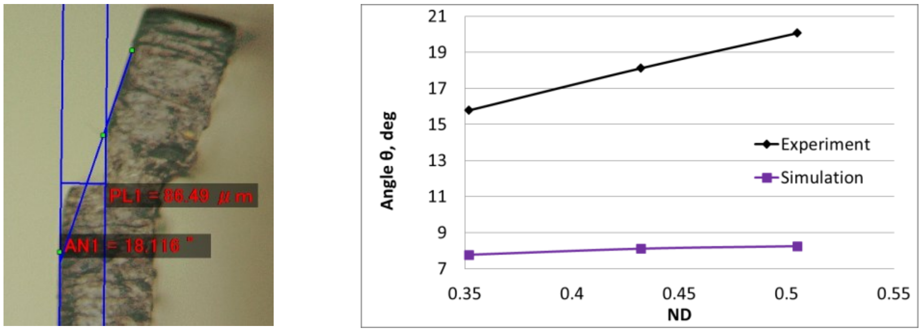
A plane strain model for the FIB process of chromium based stainless steel sheet was developed and solved using MSC Marc. The model was created according to the setup in Fig. 1 and specification of Table 1. Isotropic elasto-plastic Von Mises material model with flow stress described by the Swift hardening law fitted to uniaxial tensile test data. Most of the numerical settings are set to default values apart from a constant time step of 0.01s (cutbacks allowed) and convergence criterion of 0.001. The process involves three steps; approach of the punch, forming of the sheet and release of the tools. This initial model showed deviation from the physical results Fig 2 (b). The focus of this section is on investigation and minimization of this deviation.

Numerical Parameters

In order to improve the accuracy of the model it is necessary to first make the model stable and computationally efficient with respect to the numerical parameters and settings. A model with sample thickness of 100 µm was used to reduce CPU time. The most influential numerical aspects of the model development are discussed here.

TABLE 1. Specification of the physical test of forging induced bending.

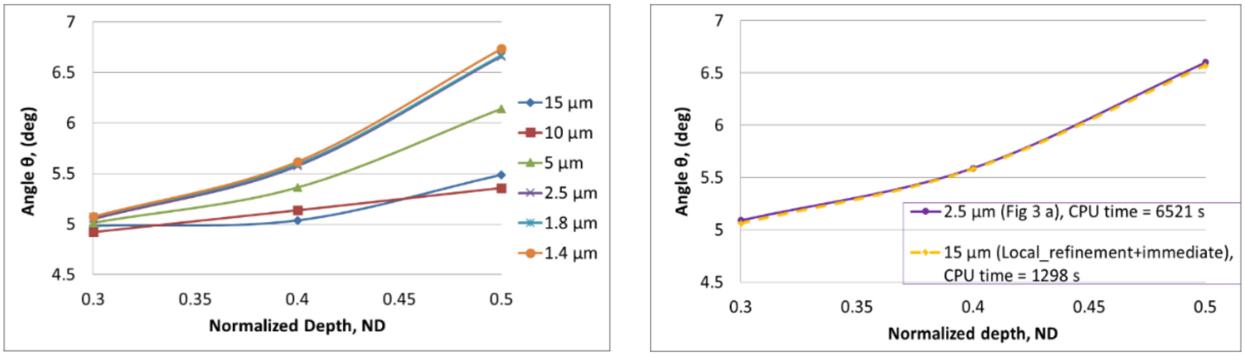
Thickness, t	Negative clearance, N_C	Punch Radius, R_P	Die Radius, R_d	Depth of impression, d
0.2 mm	0.08 mm	0.02 mm	0.05 mm	0.705, 0.865 and 0.101 mm



a) Sample measurement

b) Angle results

FIGURE 2: a) measurement of geometrical feature under microscope at 160x magnification, b) comparison of angle results.



a) Mesh size sensitivity b) Remeshing setting results

FIGURE 3: Comparison of the angle results for mesh size and remeshing settings.

Mesh Size and Remeshing

The process involve large deformation of the mesh which leads to severe distortion of the elements. To avoid this, global remeshing based on distortion of the elements is used. It will check for inner angles of the elements and perform remeshing once the limits are reached. Only distortion criterion is used for remeshing to minimize error due to data mapping as remeshing steps are kept to a minimum. In Fig. 3 (a) it can be seen that reducing the initial mesh size below 2.5 µm the change in results is negligible. Thus the result with 2.5 µm is numerically accurate, but with very high time cost. For computational efficiency refinement of the elements in the deformation zone can be performed using local adaptivity. Furthermore a criterion named *immediate* in MSC Marc can be used in conjunction with local refinement. This will refine the initial undeformed mesh locally where the deformation is about to happen. Using this procedure for remeshing will allow using a coarse initial mesh. This will reduce computation cost without affecting the accuracy as shown in comparison in Fig. 3 (b).

Time stepping

For this model load controlled steps with constant size (cutbacks allowed) is used. In case convergence is not achieved, the cutback mechanism allows scaling down the step size to improve the convergence. Generally reducing the time step size will result in increasing the computation time. On the other hand large step sizes will decrease chances of convergence, hence increasing the number of cutbacks. Cutbacks will result in extra iterations and thus increase in CPU time. For this model, step size in a reasonable range showed negligible effect on the results. An optimum value of step size was selected based on the CPU time resulting for least number of iterations performed.

Physical Parameters

After developing a numerically stable and computationally efficient model, the effect of physical parameters is investigated. The primary object of this analysis is to bring the numerical results close to physical test results. The two categories of physical parameters including material parameters and process parameters will be discussed here.

Flow behavior

First, the sensitivity of the numerical model to the input flow stress is investigated. For this purpose the flow stress given by the Swift hardening law (1) is manipulated. These fictitious manipulations are given by (2) to (4).

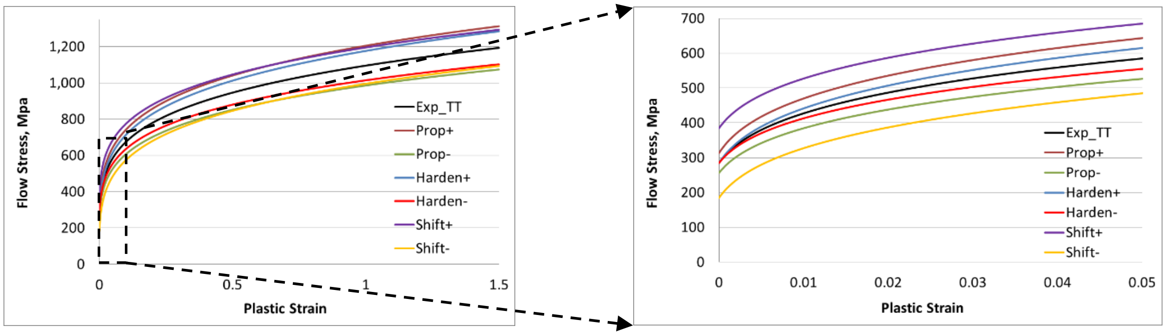
Swift hardening fit to tensile test data $\sigma = K(\varepsilon_o + \varepsilon)^n$ (1)

Proportional scaling $\sigma = (1 \pm s) * K(\varepsilon_o + \varepsilon)^n$ (2)

Hardening scaling $\sigma = (1 \pm s) * K(\varepsilon_o + \varepsilon)^n \mp s * K(\varepsilon_o)^n$ (3)

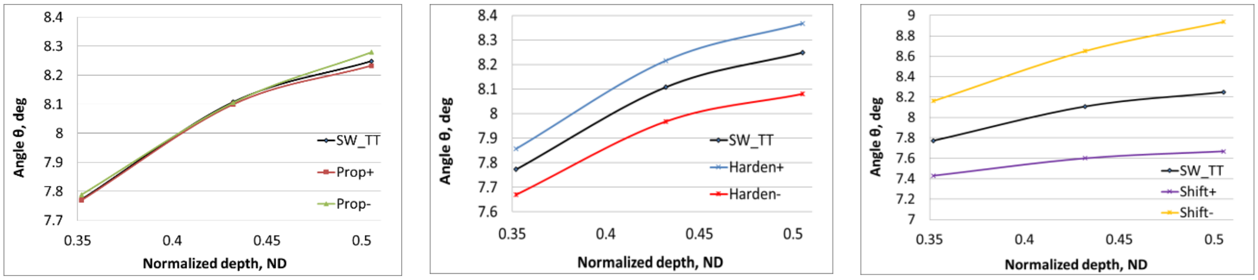
Shifting $\sigma = K(\varepsilon_o + \varepsilon)^n \pm \sigma_{shift}$ (4)

The graphical representation of such manipulation is shown in Fig. 4 and the results of manipulations in Fig. 5.



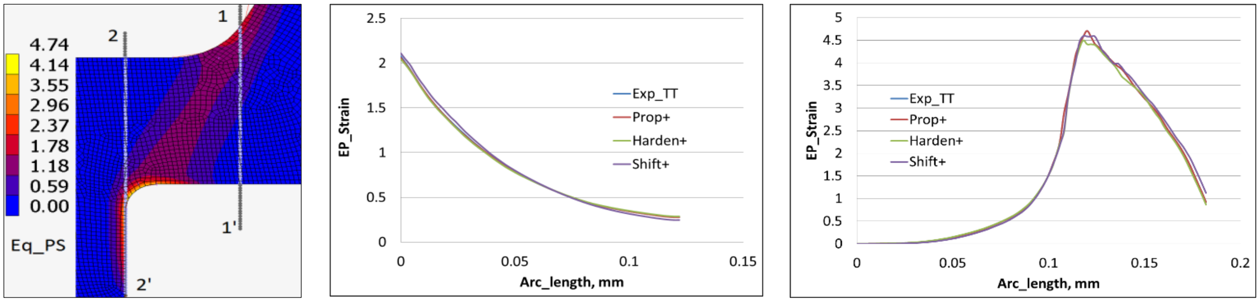
a) b)

FIGURE 4: a) Flow stress curves manipulated according to equation 1-4, b) comparison in very small plastic strain region.



a) proportional scaling b) Hardening scaling c) Shifting

FIGURE 5: Angle result comparison for different manipulation of the flow stress curve given by a, b and c.



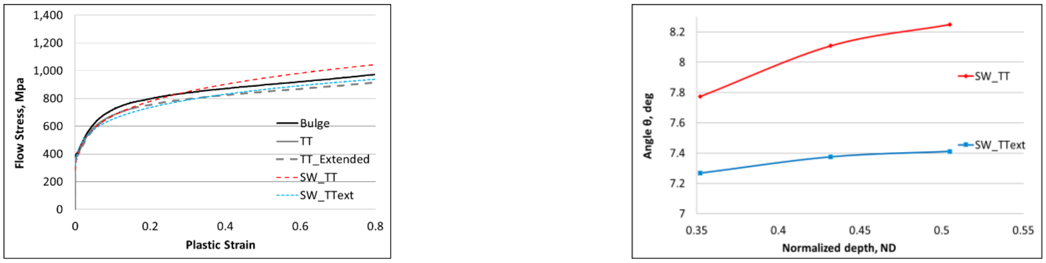
a) b) Line 1-1` c) Line 2-2`

FIGURE 6: a) Equivalent plastic strain distribution and Equivalent plastic strain distribution along b) line 1-1`, c) line 2-2`

It is observed that in all the cases the plastic strain distribution was almost the same as shown in Fig 6. Thus the difference in the results is coming from the stress distribution. The Considère relation (5) [5] can give information about stress distribution for a given plastic strain distribution as it is a relation between rate and level of stress.

$$h \equiv \frac{\partial \sigma}{\partial \varepsilon}\bigg|_{\dot{\varepsilon}} = \sigma \tag{5}$$

In case of equation (2) the flow stress and the hardening rate both are scaled proportionally, hence an identical stress distribution to the model with no scaling of flow stress is achieved. This leads to negligible effect on the angle results. This negligible effect in angle can be observed even for a very high or very low value of scaling parameter *s*. For equation (3) and (4) changing either the hardening rate or the flow stress level would affect the stress distribution. This stress distribution change has resulted in change in angle result for using the manipulation of (3) and (4) as can be seen in Fig. 5 b) and c). From this discussion it is clear that accurate prediction of flow stress curves from experimental data is important. For this purpose the extended flow stress curves from the MEGaFiT project [6] for CS steel is fitted. The fitted curve and the resulted angle comparison is shown in Fig. 7.



a) b)

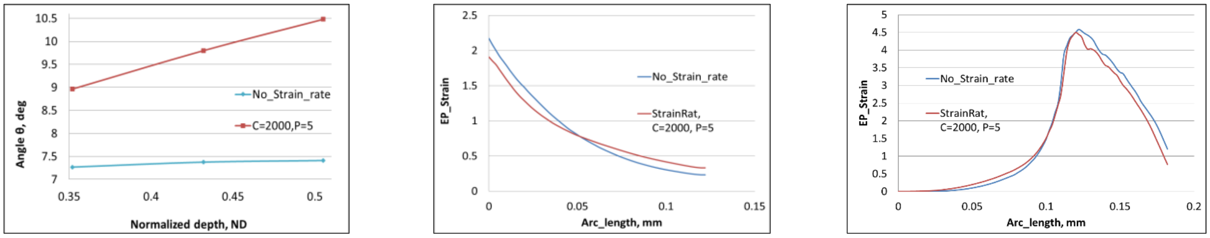
FIGURE 7: a) Correction of flow stress fit with extended experimental data. b) Angle results comparison

Strain rate

From Fig. 6 (a) it can be seen that physically the process involves very high plastic strains achieved in short time. Thus it is necessary to include the strain rate effects in the material model. For this purpose Cowper and Symonds strain rate model [7] is used in which the flow stress is scaled by a factor given by (6). The parameters are taken as C=2000 1/s and p=5 from thesis [8] for AISI 430 steel which is similar to steel used here. Assuming the physical process takes 0.1 s to complete, the strain rate effect is accounted for. The results of the angle are shown in Fig. 8 a).

$$1+\left(\frac{\dot{\varepsilon}_{pl}}{C}\right)^{1/\mathrm{p}} \qquad (6)$$

The reason for this large deviation is due to big difference in the plastic strain distribution as shown in Fig. 8 b) and c). In previous section it was observed that for same plastic strain the material behavior was affected by the stress distribution and bringing change in angle. Strain rate effect itself is a proportional scaling of the input flow stress, which should not affect the angle results. But since the part is not uniformly deformed and will lead to different strain rate scaling in different area of the part. This will affect the kinematics of the process leading to differences in plastic strain distribution and hence the influence on the angle results.



a) b) Line 1-1` c) Line 2-2`

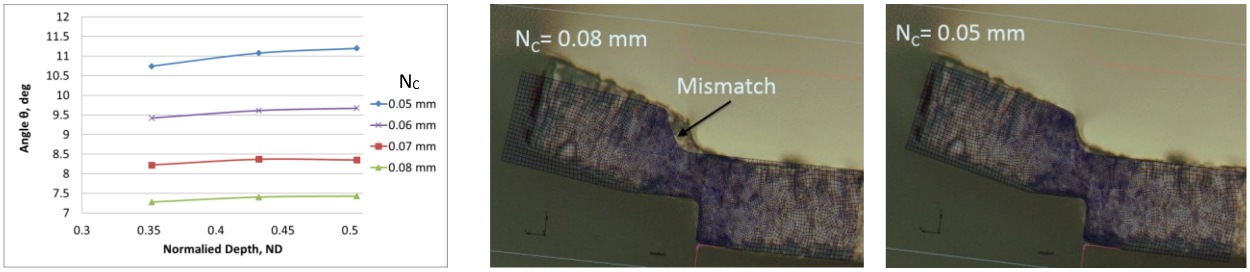
FIGURE 8: Effect of the strain rate on the angle results for forging induced bending and Equivalent plastic strain distribution comparison with and without strain rate formulation along b) line 1-1`, c) line 2-2`

Geometric validation

From the previous section, it can be seen that plastic strain distribution has high impact on the angle results. Process parameters affect the kinematics of the process which in return describes the plastic strain distribution. The effect of one such parameter N_C is discussed here. This effect is plotted in Fig. 9 a). This effect is coming from the change in the plastic strain distribution. Due to high sensitivity of the angle to variation in negative clearance, a comparison is made of the deformed FEM mesh geometry with the physical part. It was found in the mapping that using N_C = 0.08 mm there is a mismatch between the FEM mesh and physical part. Reducing N_C to 0.05 mm the mesh geometry is matching the physical part as shown in Fig. 9 b) and c). This indicates a discrepancy in the alignment of the tools, leading to an incorrect negative clearance in the press, which will be investigated.

Finally combining all the above corrections for input flow stress, strain rate, and negative clearance the model results are compared with physical test results in Fig. 10. Improvement in the results can be seen but there are still deviations. Further improvement of the model will be;

1. Proper implementation of the anisotropy, as the tests of steel used have shown presence of anisotropy.
2. Since radii of the tools are in the range of 20-50 μm, limited number of grains are interacting with the tools. This will require to model the size effects due to weak surface grains and due to presence of the high local plasticity gradient near the tool contact and in the width of the plastic strain band Fig. 6 a).



a) b) c)

FIGURE 9: a) Results for variation in N_C, b) and c) Mapping of the FEM and physical part geometry.

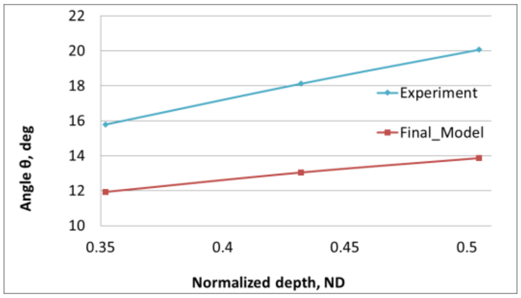


FIGURE 10: Comparison of angle results of experiment and final developed model for FIB process

CONCLUSIONS AND FUTURE WORK

A numerically stable and efficient model for the suggested FIB process is developed. Effects of the physical parameter variations are investigated to check for the discrepancy between the model and the experiment. The analysis revealed that process parameters that govern the kinematics and as a results the plastic strain distribution, have a major influence on the variation in results. While the material parameters affect the results through their influence of the stress distribution. Future work will involve further improvement of the numerical model by implementing material anisotropy, and size effects due to the tool features.

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