EFFECTS OF MATERIAL ORIENTATION ON AIR BENDING OF INTERSTITIAL FREE STEEL SHEET

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ABSTRACT

In this work, material orientations which affect bending behavior of Interstitial Free (IF) steel sheets that are subjected to air bending process have been studied. A detailed experimental study of air bending process was carried out considering various orientations namely, 0^0,45^0 and 90^0 to the rolling direction. The tensile tests were carried out for the three orientations to determine the material properties related to bending process. The chemical composition and microstructures for bend and unbend regions were obtained. The effect of orientations on punch load, bend angle, springback and obtained results were discussed in detail. It is observed that the 0^0 samples experience larger springback than the 45^0 and 90^0 test samples. It is generally found that the springback exhibited a polynomial relationship with the punch travel. A statistical analysis has been carried out to determine the appropriate deviation in the material model.

Keywords: Air bending, IF steel, Springback

1. Introduction

The sheet metal forming industry has become one of the major manufacturing sectors for the automobile, aircraft and electrical industries. Press brake forming is a sheet metal forming process in which the workpiece is placed over an open die and pressed down into the die by a punch. The primary advantages of the press brakes are versatility of manufacturing various product configurations in a single setup and low tooling costs. Low carbon steels, high strength low alloy steels, stainless steels and aluminum alloys are commonly formed in press brakes.

In air bending, the required angle is produced on the workpiece by adjusting the depth of the punch entering the die opening. The required angle can be obtained by over bending the metal sufficiently to compensate the springback. Changing the size of the die opening also changes the amount of force needed to bend. As the die opening increases, the force required for bending decreases and vice versa. This process is chosen for analysis because its flexibility and reduction in punch load are excellent.

The sheet material used in this investigation is Indian Interstitial Free steel owing excellent formability. Vacuum degassed steels [1] containing very small amounts of titanium and niobium are known as interstitial free steels. Since these additions combine with interstitially dissolved atoms of carbon and nitrogen and form separate precipitates of TiC, TiN and NbCN, no carbon or nitrogen remains in ferrite solid solution. The product has very low yield stress combined with a high ductility. In the metal forming industries, the knowledge and proper control of the springback after forming are the fundamental aspects in the achievement of Near-Net-Shape parts. Springback refers to the change in the shape of the sheet geometry after the load has been removed. It is one of the key factors influencing the quality of sheet metal manufacture. It is encountered in all forming operation, but it is most easily recognized and studied in bending. It leads to major problemsduring the assembly and it complicates the die design process. Springback behavior of sheet materials [2] depends on the properties of materials used such as Young's modulus, yield strength, plastic strain ratio and its anisotropy, strength coefficient and sheet thickness. During rolling process and subsequent annealing [3], the grains and any inclusions present become elongated in the rolling direction and a preferred crystallographic orientation develops. This causes a variation of properties with direction and this is called anisotropy. Since the properties vary with orientation of the rolling sheet, it influences the tensile properties and hence the bending behavior. Considerable investigations have suggested the importance of considering the orientation in sheet metal forming. The bending angle and punch profile radius significantly effects the springback behavior [4]. The springback varies with even a small change in punch profile radius. The punch velocity and width of the sheet play a significant impact on the bend angle [5].

Reviewing the literature, it is found that researchers have been studying the phenomenon of springback for nearly four decades. Hill [6] illustrated a

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mathematical theory of plastic bending of plates under plain strain condition. Yu et al. [7] examined the influence of strain hardening on bending behavior of strips. Wang et al. [8] described a complete mathematical model for plane strain sheet bending to predict springback and the maximum bending load on the punch and die. A simple approach for calculating bendability and springback in bending based on the normal isotropic value, strain hardening exponent and sheet thickness has been presented as described elsewhere [9]. You-Min Hang et al. [10] described effects of process variables like punch radius, die radius, punch speed, friction coefficient, strain hardening exponent, normal anisotropy on V-die bending process of steel sheet. Elkins et al. [11] developed an analytic bending model, which provides insights into the material and geometric variables that effect springback. Aleksy. et al. [12] conducted experiments on springback for dual phase steel and conventional high strength steel for a hat channel section with varying cross sections. They described the methodology of experiments and discussed springback related results. Draw bend test for various die radii, friction coefficients and tensile forces was conducted by Cardeen [13]. Perduijn et al. [14] derived a simple explicit bending couple curvature relation for small and larger curvatures and they verified the model with experimental results.Zhang et al. [15] developed a new model for strain calculation in plane strain bending and also compared with Hill's pure bending model. Mai Huang et al. [16] presented a literature review of the springback of doubly curved developable sheet metal surfaces and provided a bibliography on the springback in sheet metal forming. Livatyali et al. [17] presented experimental investigation to determine the influence of die corner radius, punch radius, punch – die clearance, pad force and sheet material on springback in straight flanging. The accuracy of modifications of the algorithms was verified by experimental results. Lumin Geng et al.[18] reported springback angles and antielastic curvatures for a series of draw bend tests using an anisotropic hardening model and sheet metal yield functions. Weilong Hu [19] proposed anisotropy hardening models with simple loading conditions that include exponential hardening model, linear hardening model and multi linear hardening model. Gary Harlow et al. [20] described the probability modeling to estimate variability in the dimensions of a component and the effect of stress-strain behavior; the model parameters and the statistical variability in material properties on springback are evaluated.Zafer Tekiner[21] examined the springback of sheet metals with various thicknesses and properties in bending dies.Carlos Gomes et al.[22] investigated the variation of springback in high strength steels based on experimental and numerical analysis.Jenn-Terng Gau et al.[23] proposed a model for springback prediction for aluminum sheet forming and material parameter is presented to handle the Bauchinger effect.Ozgur Tekaslan et al.[24] carried out the experiment to determine springback of steel sheet with V-shaped die. Peng Chen et al.[25] studied to predict the variation of springback in an open channel drawing considering the variation of material and process. Hyunok Kim et al. [26] proposed an analytical model to predict springback and bend allowance simultaneously in air bending process.

Due to the lack of literature available on springback behavior of Indian IF steel sheets, the present work has been undertaken. Most of the earlier studies have been made on smaller curvature bending $\left(R_c/t \leq 5\right)$ to explore various parameters on springback during air bending process. The present experimental investigation is an attempt to find the effect of orientations namely, 0^0,45^0 and 90^0 material orientations, for larger curvature bending $\left(R_c/t \geq 5\right)$ on punch load, bend angle and springback of Indian IF steel. This paper also investigates the accuracy of the material model and the statistical variability in the above parameters on springback is assessed.

2. Experimental Details

2.1Chemical Composition and Tensile Test

The chemical composition of Indian IF steels used in the analysis are given in Table 1.

Table 1:Chemical Composition of IF Steel (in wt %)

C	0.0035
Mn	0.4
Si	0.008
S	0.007
P	0.044
Al	0.045
N	35
Ti	0.04
B	0.0008
Nb	0.001
Fe	Rest

Table2 :Tensile Test Data of IF Steel of Thickness 1.2 mm

Test data/ Units/ Notation	Orientation Related to Rolling direction			$Average^*$
	90º	**45º**	**0º**	
Strain Hardening Exponent (n)	0.307	0.325	0.310	0.317
Strength Coefficient MPa (K)	595.8	603.3	628.7	607.8
Yield Strength MPa (σ_y)	220	216	267	229.8
Ultimate Tensile Strength MPa (S_{ut})	326.1	324.8	322.2	324.5
Plastic Strain Ratio (r)	1.3	1.55	1.15	1.39
Young's Modulus GPa (E)	207	207	207	207

(Note: Data represents average values only)

$$Average^* = \frac{X_{0^o} + 2X_{45^o} + X_{90^o}}{4}$$,where X is n-value or K-value or σ_y-value or S_{ut}-value or r-value or E-value.

To investigate the effect of orientation, three orientations were considered in this analysis. One is along the rolling direction (0^0), another is transverse to the rolling direction (90^0) and third one is diagonal to the rolling direction (45^0). The main parameters namely the strain hardening exponent (n), strength coefficient (K), yield strength (σ_y), ultimate tensile strength (S_{ut}), plastic strain ratio (r) and its normal anisotropy $(\bar{r})$ along the three orientations were obtained from the tensile test and the average values were determined. The data are listed in **Table 2.** It is observed that for each specimen orientation there is a different r-value and it indicates that the sheet anisotropic properties depend on the orientation to the rolling direction.

2.2 Experimental Procedure

2.2.1 Sample Preparation

The dimensions of test samples were of 120mm x 40mm. Thickness of sheets were of 1.2mm. The samples were prepared from the cold rolled and annealed sheet as per the ASTM standards. The stock from which blanks were cut must be flat enough so that the blanks could be properly inserted into the tooling and remain in position during forming. The samples were cleaned thoroughly to remove the dust and rust by wiping.

2.2.2 Experimental Setup

The experiments were performed in a Universal Testing Machine (UTM) and the experimental setup consisted of a die and a punch of hardened steel. The die was mounted on the fixed platform provided on the UTM. The punch was mounted above the die on the movable head of the UTM. The center axis of the punch coincided with the die. The sample was located in proper position over the die with extreme care. The load was applied gradually and depth was given in incremental steps to deform the sheet.

Table3: Tooling Geometries and Process Parameters Used

Die radius (r_d) in mm	5
Die opening (w_d) in mm	60
Punch radius (r_p) in mm	8
Punch width (w_p) in mm	90
Sheet material	Interstitial Free Steel Sheet
Strip dimensions $(L \times w \times t)$ in mm	120 x 40 x 1.2
Orientations of the sheet	0º,45º and 90º
Punch travel (d) in mm	0 – 30
Punch velocity (v_p) in mm/s	0.3577

The tooling geometries and process parameters used in the experiments are listed in Table 3. The tooling arrangement used in the experiments is shown in Fig .1.

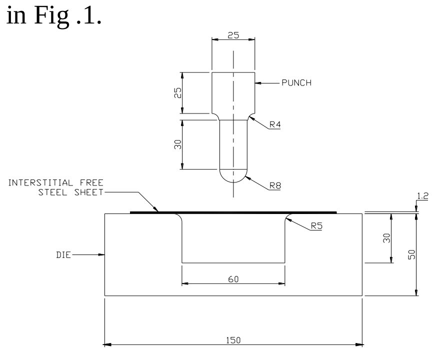


Fig.1 Schematic Diagram of the Experimental Setup

2.2.3 Measurement of Punch Load, Punch Travel and Springback Angle

The punch load for bending and punch travel was recorded from the dial indicator and digital meter of UTM respectively. The larger edge of the bent sample was coated with black ink and the impression of the bend profile was taken on a white paper. Then the load was removed and again the impression of the profile was taken. The impression images were scanned and digitized. The angles of the digitized images were measured using CAD software [13]. The difference between bend angles $(\theta_1 \approx \theta_2)$, when the sample was subjected to load (θ_1) and after removal of load (θ_2) gives the springback angle. The above steps were repeated for each incremental punch displacement until the total depth was reached. For the springback measurement, ten values were taken for each orientation conditions $(N = 10)$.

2.2.4 Metallographic Study

The microstructure of Indian IF steel considered for the study was obtained by the following standard metallographic procedure. The specimens for metallographic study were cut from the test samples at undeformed and plastically deformed regions of all three orientations. The specimens were mounted in bakelite material and polished. Then the nital etchant solution was applied over the surface of the specimens and studied under the metallurgical microscope with the magnification factor of 200X**.**

3. Theoretical Aspects

The theoretical analysis presented in this paper only concerns the material model on springback ratio ($\Delta\theta$ / θ).

Samuel elsewhere [27] proposed springback ratio as follows:

$$\frac{\Delta\theta}{\theta} = \left(\frac{\frac{1}{\rho}-\frac{1}{\rho^*}}{\frac{1}{\rho}}\right) = K\left(\frac{1+R}{\sqrt{1+2R}}\right)^{1+n}\left(\frac{3(1-\gamma^2)}{2E(1+n)}\right)\left(\frac{t}{2\rho}\right)^{n-1} \quad (1)$$

For simplicity, the elementary bending theory is adopted to analyze the deformation of elastic unloading. To find appropriateness of the material model, a statistical analysis was proposed by Li [28]. In this method, the standard deviations were computed on the basis of calculated and measured springback angles as follows

$$\langle\sigma\rangle = \sqrt{\frac{\Sigma_{i=1}^{N}\left(\Delta\theta^{i}_{measured} - \Delta\theta^{i}_{calculated}\right)^2}{N}} \quad (2)$$

4. Results and Discussion

4.1 Microstructure Observations

Fig. 2 (a) **-** (f) show optical microstructure of the specimen before and after deformation at the bending region to a level of bend angle of 90^0 with punch velocity and punch radius 0.3577mm/s and 8mm respectively. The microscopic examination indicates that the sample exhibits less homogeneous deformation at all conditions (90^0,45^0 and 0^0 orientations). Further, the microstructure at bend and unbend region are not uniform. The photomicrograph of IF samples show spheriodised iron carbide (cementite) particles in the microstructure.

4.2 Effect of Orientation

From Fig. 3 (a), it is noted that irrespective of the orientations, initially the punch load increases with punch travel rapidly and after a maximum value is reached, it decreases for further punch travel provided that the punch radius and punch velocity are kept constant. It is further observed that the effect of orientation is quite dominant in the latter part than in the initial stages. Comparing the three orientations, the punch load required is higher in the case of 90^0 ,lower in the case of 45^0 and 0^0 lies in between them. The reason is that for 90^0 degree orientation the value of strain hardening exponent is to be lower. The relation between punch load and punch travel is found to be polynomial. All the punch load-punch travel curves for the different combinations exhibit similar characteristics (as shown in figures) which provide a good basis for selecting the largest punch load in a pressing machine [30].

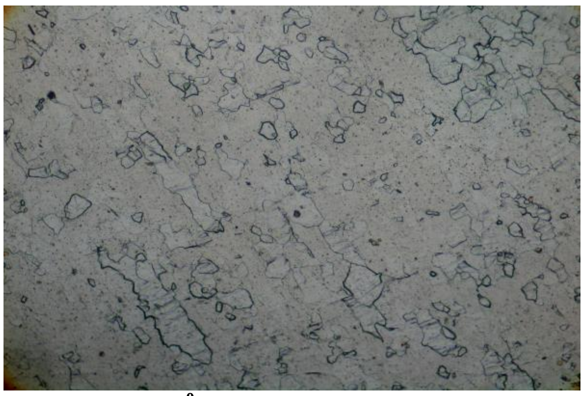


Fig.2 (a).90^0 Orientation-unbend region

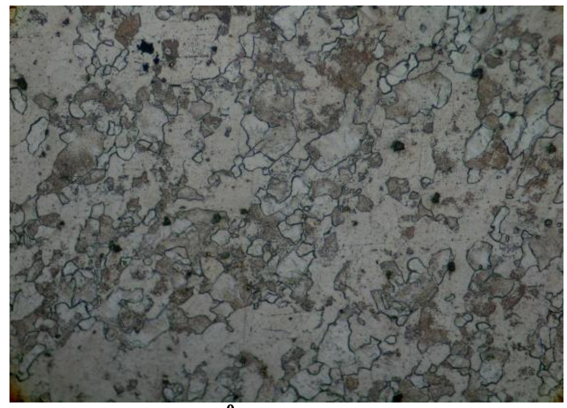


Fig.2 (d).45^0 Orientation-bend region

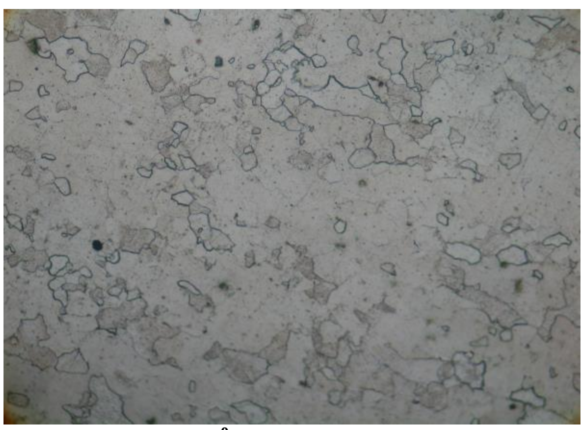


Fig.2 (b).90^0 Orientation-bend region

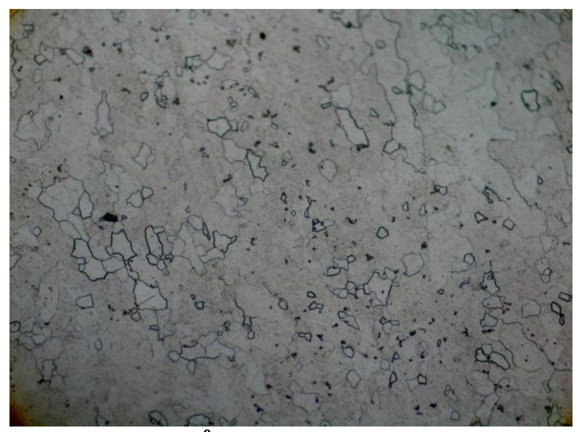


Fig.2 (e).0^0 Orientation-unbend region

Fig.2(c).45^0 Orientation-unbend region

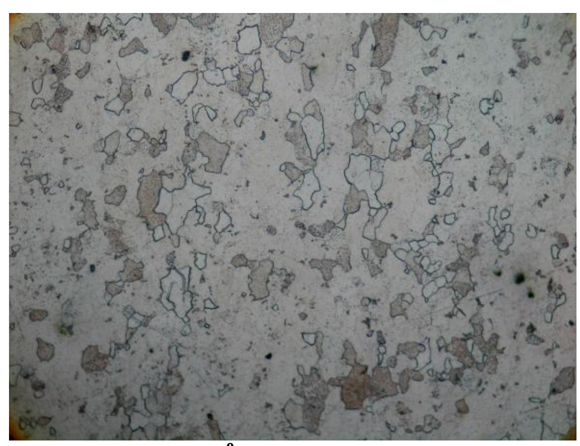


Fig.2 (f).0^0 Orientation-bend region

Fig .2 (a)-2(f) Microstructure of IF steel of 90^0 45^0,0^0 orientations for unbend and bend region at magnification 200 X

Fig. 3 (b), the change of bend angle with respect to punch travel does not exhibit any significant variation for the orientations investigated. The relationship between bend angle and punch travel is a polynomial behavior provided that the punch radius and punch velocity are kept constant.

Fig.3(a)Variation of different punch loads with respect to the punch travel for orientations

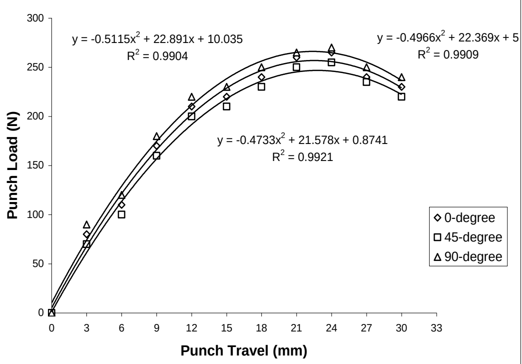


Fig.3(b) Variation of different bend angles with respect to the punch travel for orientations

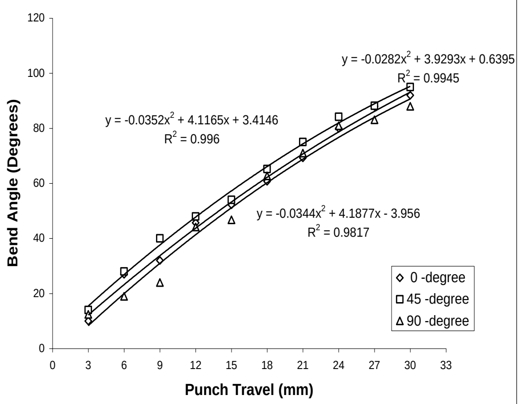


Fig.3(c) Variation of different springback with respect to the punch travel for orientations

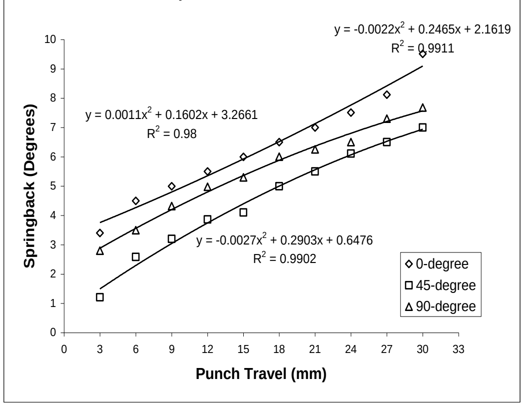


Fig.3(d) Variation of different springback angles with respect to the bend angle for orientations

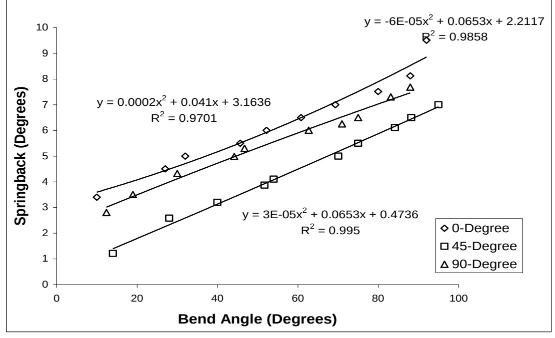


Fig.4(a) Variation of different springback angles with respect to the punch travel for comparison(0-Degree orientation and standard deviation=4.6526)

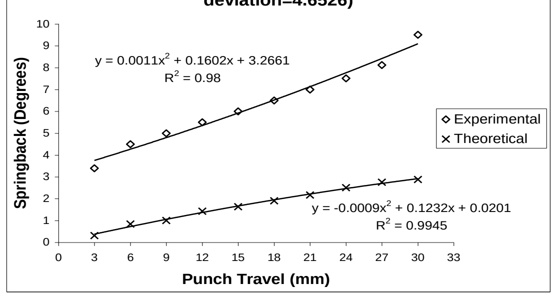


Fig.4(b) Variation of different springback angles with respect to the punch travel for comparison (45-Degree orientation and standard deviation=2.9342)

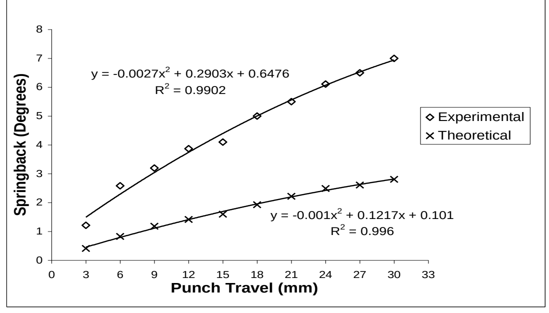
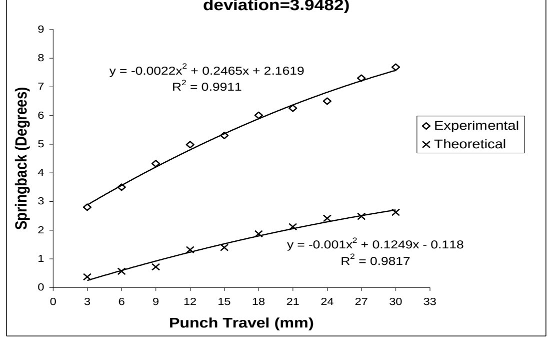


Fig.4(c) Variation of different springback angles with respect to the punch travel for comparison (90-Degree orientation and standard deviation=3.9482)



It is observed that the orientation has a great effect on the springback. It is observed from Fig. 3(c), the springback values are in the ascending order for 45^0 ,90^0 and 0^0 orientation. This is due to the fact that the springback is a function of yield strength to Young's modulus ratio [as per Ref.4, 22, 29] and in this case the ratios are 0.002043, 0.0012898 and 0.001062 for 45^0, 90^0 and 0^0 respectively. (Refer Table 2).For instance, it is evident from the ratio that when the size is same, 90^0 and 0^0 are more bendable [29] than 45^0.

Fig. 3 (d) illustrates the variation of springback with respect to different bend angle of the sheet. It can be seen that the springback increases with increase of bend angle and reveals the upward trend. It is well known the larger is the bend angle, the larger is the bending moment, and therefore bigger is the springback [4].This trend can be noticeable in all the orientations. This figure also showing the effect of orientation on springback.Here also the springback values are in the ascending order for 45^0,90^0 and 0^0 orientation. It has been observed that springback changes depending on the orientations. Thus the final shape of the sheet is influenced by the material properties.

4.3 Comparison with Material Model for Springback

The material model suggested [27] was used in the analysis of smaller curvature bending and it gives better agreement with experimental results. To find appropriateness for larger curvature bending, Li's statistical analysis [28] has been carried out.

Fig. 4 (a)-(c) show the variations of springback as a function of punch travel curves are shown for three orientations (0^0,45^0 and 90^0) for comparison. In this calculated springback value from material model (calculated) and experimental springback values (measured) are used. In the case of material orientation, 45^0 show a small deviation of springback (2.9342), whilst for 0^0 a larger deviation (4.6526) occurs. The standard deviation of springback value is 3.9482 for 90^0 orientation to the rolling direction. From the statistical analysis, it is found that there is a significant value of standard deviation of springback irrespective of orientations. These results show that there are inaccuracies in the material model and it is not capable of predicting the springback accurately for larger curvature bending. By examining the material model, the springback is much influenced by the strength coefficient and modulus of elasticity [22]. But many other parameters such as punch radius, punch velocity, friction and width of the sheet also influence the springback [10]. This may be the reason for the higher deviation.

5. Conclusions

Based on this investigation, the following conclusions can be drawn:

1. The orientation influences the punch load, bend angle and springback significantly. From the experimental results, it is clear that the influence of process variables on all three orientations of IF steel samples are very significant provided that the punch radius and punch velocity are kept constant.
2. The relationship between springback and bend angle of the sheet exhibited to a polynomial behavior for all the cases. The experimental springback findings for the IF steel sheet are also compared with material model. The standard deviations between the experimental springback and material model springback are noted to be very large. The springback variation is a strong function of the process parameters in larger curvature bending.

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Nomenclature

E	Young's Modulus	MPa
K	Strength Co-efficient	MPa
N	Number of Measurements	-
n	Strain Hardening Exponent	-
w_p	Punch Width	mm
R_c	Radius of Contact	mm
r	Plastic Strain Ratio	-
R	Normal Anisotropy	-
r_d	Die Radius	mm
r_p	Punch Radius	mm
L	Length of the sheet	mm
d	Punch Travel	mm
t	Thickness of the Sheet	mm
v_p	Punch Velocity	mm/s
w	Width of the Sheet	mm
w_d	Die Opening	mm
$\langle\sigma\rangle$	Standard Deviation	Degrees
σ_y	Yield Strength	MPa
S_{ut}	Ultimate Tensile Strength	MPa
γ	Poisson's Ratio	-
ρ	Radius of Curvature	1/mm
$\Delta\theta^i_{measured}$	Measured Springback Angle	Degrees
$\Delta\theta^i_{calculated}$	Calculated Springback Angle	Degrees
θ_s	Springback Angle $(\theta_1 \approx \theta_2)$	Degrees
θ_1	Bending Angle before Springback	Degrees
θ_2	Desired Bending Angle after Springback	Degrees