International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:10, 2010

Springback Simulations of Monolithic and Layered Steels Used for Pressure Equipment

Anish H. Gandhi, and Harit K. Raval

Abstract**—**Carbon steel is used in boilers, pressure vessels, heat exchangers, piping, structural elements and other moderate-temperature service systems in which good strength and ductility are desired. ASME Boiler and Pressure Vessel Code, Section II Part A (2004) provides specifications of ferrous materials for construction of pressure equipment, covering wide range of mechanical properties including high strength materials for power plants application. However, increased level of springback is one of the major problems in fabricating components of high strength steel using bending. Presented work discuss the springback simulations for five different steels (i.e. SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B) using finite element analysis of air V-bending. Analytical springback simulations of hypothetical layered materials are presented. Result shows that; (i) combination of the material property parameters controls the springback, (ii) layer of the high ductility steel on the high strength steel greatly suppresses the springback.

Keywords**—**Carbon steel, Finite element analysis, Layered material, Springback

I. INTRODUCTION

CARBON steel is most widely used ferrous material for fabrication of pressure equipments and structures. While selecting the materials for particular application, along with strength and ductility criteria, factors like cost, availability and ease of fabrication are equally important. ASME Boiler and Pressure Vessel Code, Section II, Part A (2004) [1] provides specifications of ferrous materials used for construction of pressure equipment, covering wide range of mechanical properties including high strength materials for power plants application. Bending/forming of the ferrous materials is one of the essential requirements for fabricating the pressure equipment. However, increased level of springback is one of the major problems in fabricating components of high strength steel using bending/forming. Table I shows the mechanical properties of the five different grades of ferrous materials used for the presented study namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B, suitable for the different applications. Strength coefficient (K) and strain hardening exponent (n) reported in Table I are calculated based on stress at ultimate point [2]. Table II shows the classification of ferrous materials based on yield strength (σ_y) [3]. Out of the different ferrous materials reported in Table I, SA-299 and SA-612 are high strength ferrous materials and SA-724 is extra high strength ferrous material.

Use of the high strength steel is gaining its importance in the engineering construction from the point of view of reducing the weight of the structure and increasing cost effectiveness. ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 (2001) [4] provides rules for construction of various components of the pressure equipment. For the pressure vessel shells, difference of the maximum and minimum inside diameters at any cross section should not exceed one percent of the nominal diameter. Hence, to ease the fabrication of the pressure equipments out of high strength and extra high strength ferrous materials maintaining the required dimensional accuracy, two basic issues needs to be address; (i) controlling or suppressing the springback during bending/forming and (ii) prediction of springback for setting the process parameters to obtain required product dimensions.

Literature review reveals that many different manufacturing techniques were used to control the springback. Use of the binder force is one of the techniques employed by the researches. Sensuri et al. (1996) [5] reported that a variable binder force history during forming operation can reduce springback amount while maintaining a relatively low maximum strain. Ruffini and Cao (1998) [6] and Cao et al. (1998) [7] proposed neural network based models to minimize the springback in channel forming process. Cao et al. (1998) [7] reported that stepped binding force can reduce the springback significantly.

Though springback can be controlled it can't be eliminated and hence, its accurate prediction is important. Analytical as well as numerical models are reported by many researchers for springback prediction.

Dr. A. H. Gandhi is an Assistant Professor in mechanical engineering at C. K. Pithawalla College of Engineering and Technology, Surat 395 007, Gujarat, INDIA. His research area includes Metal Forming Analysis, Computer Aided Manufacturing, Application of AI to Manufacturing and Design of Experiments (corresponding author; phone: (M) +91 9374519605, (O) +91 261 2728282, (R) +91 261 2766265; fax: +91 261 2723999; email: anishgandhi2002@yahoo.co.in).

Dr. H. K. Raval is Professor in engineering at S. V. National Institute of Technology, Surat 395007, Gujarat, INDIA. His research area includes Metal Forming Analysis, Metal Cutting, Advance Manufacturing Processes, Computer Aided Manufacturing and Computer Integrated Manufacturing (email: hkr@med.svnit.ac.in).

TABLE I
SPECIFICATIONS OF THE CARBON STEEL PLATES FOR PRESSURE VESSELS [1]

Material Type	Grade	Tensile strength (σ_t) (Nmm^{-2})	Yield strength (σ_y) (Nmm^{-2})	*Percentage elongation (2”)	Strain hardening exponent (n) (2")	Strength coefficient (K) (Nmm^{-2}) (2") low range
SA - 36	-	400-500	250	23	0.21	554
SA - 299	-	515-655	290	19	0.17	698
SA - 515	70	485-620	260	21	0.19	665
SA - 612	-	570-725	345	22	0.20	786
SA - 724	B	655-795	515	15	0.14	862

* Percentage elongation (2”): Percentage elongation measured over 2” long specimen

TABLE II
CLASSIFICATION OF FERROUS MATERIAL BASED ON YIELD STRENGTH (Σ_Y) [3]

Class	Yield strength range (N/mm^2)
High strength	290-482
Extra high strength	414-759
Ultrahigh strength	897-2413

Wang et al. (1993) [8] reported elasto-plastic mathematical models based on Swift’s strain hardening law for plain-strain sheet bending to predict; spring back, bendability, strain and stress distributions and the maximum loads on the punch and the die. Date et al. (1999) [9] reported the process model to asses the effect of different geometric and material parameters on the springback in the air V-bending process. Sensitivity of springback to strain hardening exponent (n) was studied in the light of four factors influencing springback namely strength of material (σ_y), tensile strength, strength coefficient (K) and Young's modulus (E). They concluded that the sensitivity of the springback depends on the combinations of these parameters. Vin (2000) [10] presented the model for accurate prediction of curvature in air bending specially under the punch nose. Reported method was based on the concept of minimization of bending energy by eliminating the assumption of wrap around and can be used for the adaptive control of the process. Gau and Kinzel (2001) [11] investigated the influence of Bauschinger effect on springback in sheet metal forming based on experiment on three different kinds of steel sheet (high strength, back hard and AKDQ) and aluminum sheet (AA6111-T4) metal. Carlos et al. (2005) [12] investigated variation in springback of high strength steel due to material anisotropy. Plasticity model based on Barlet's yield criteria, Hill's transverse anisotropic model and Von Mises' yield criteria was used for the numerical analysis of springback in bending U shape form. Satorres (2005) [13] reported the FE analysis of air bending with Ansys LS-DYNA and reported that 10 times to 100 times mass scaling can be used to reduce solution time without major effect on results. He also reported that the velocity scaling can be used for further reduction in solution time but real velocity should be used to get accurate results. Verma and Haldar (2007) [14] investigated the effect of anisotropy on springback using analytical and FE model for the benchmark problem of Numisheet-2005. Kim et al. (2007) [15] reported the analytical model to predict springback and bend allowance in air bending considering effect of neutral line shift, thickness reduction, radial stress, Swift’s equation, anisotropy, die geometry and friction effects. Gandhi and Raval (2006, 2008) [16], [17] reported the analytical model for estimation of top roller position as a function of desired radius of curvature, for multiple pass 3-roller forming of cylinders, considering Ludwik-Nadai pre strain power law and change of Young's modulus (E) during the deformation. Further, they reported development of empirical correlation for machine setting parameters for cylindrical bending.

In practice, though high strength steels with good balance of strength and ductility are produced successfully by controlling the chemical composition and microstructure, increase in the strength of the steel is detrimental to ductility. To overcome this difficulty, researchers are attempting to develop layered high strength steel materials with improved formability. Verguts and Sowerby (1975) [18] reported analysis of pure bending of laminated sheet and discuss the influence of the individual laminates on bending process. They reported the analytical model for prediction of sheet thickness, bending moment, and distribution of radial and tangential stresses across the sheet as a function of radius of curvature of bent sheet. They concluded that relative position of strong and weak constituent in the sheet laminate influence the bending mechanics. Majlessi and Dadras (1983) [19] presented analysis of pure plastic bending of two and three-ply laminates in plane strain condition based on rigid strain hardening behavior. They also investigated the effect of material properties in terms of core/clad strength difference, rate of strain hardening and laminate geometry on bending mechanics. Kim and Yu (1997) [20] review the technological status of coated, clad, laminated and sandwich sheets including their formability, mechanical performance, fracture behavior and applications. Hino et al. (2003) [21] investigated springback of two-ply sheet metal laminates (pure aluminum (JIS A1100) and ferritic steel (JIS SUS430)) subjected to draw bending using numerical and experimental techniques. Yilamu et al. (2010) [22] presented sheet thickness change, bending angle and springback phenomena of a stainless steel clad aluminum sheet in air V-bending. Based on the experimental observation, it was reported that sheet-set condition (i.e. stainless steel in and aluminum out or vise versa) greatly influence the shape and angle of bent sheet, but its effect on springback is negligible. They concluded that modeling of the Bauschinger effect is essential for the accurate simulation of springback of clad sheet metals. Tetsuo et al. (2010) [23] evaluated bending formability of multilayered steel sheets by tensile tests, V-bending tests and hemming tests. Reported experimental result shows enhanced formability of multilayered steel material in comparison to its high-strength material constituent. They reported two dimensional solid-element finite elements (FE) modeling of geometrical features of a multilayered steel sheet under an isostrain condition, adopting rule of mixtures to obtain the flow curve of the constituent high-strength material. Reported work discusses the layer arrangement for reducing the springback angle based on the FE analysis of multilayered steel sheets undergoing V-bending.

Many researchers address the methods for controlling springback, analytical and numerical models for prediction of springback and study of the effect of various material property, geometry and process parameters on springback. As high strength materials are specified by high yield strength (σ_y), low strain hardening exponent (n) and high strength coefficient, effect of combined variation of material property parameters on the springback needs to be investigated. Presented work discusses the two dimensional FE simulations of air V-bending to study the springback phenomena of five different ferrous materials namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B, suitable for the different pressure equipment applications. Further springback for hypothetical layered ferrous material made of constituents SA-36 (high ductility steel) and SA-724 grade B (extra high strength steel) is evaluated assuming superimposition of analytical internal bending moment of individual constituents and linear elastic recovery law. Analytical internal bending moment and hence springback prediction for layered ferrous material was based on analysis reported by Gandhi and Raval (2008) [17]. Analytical models for internal bending moment and springback for larger bend radius to thickness ratio proposed by Gandhi and Raval (2008) [17] is reported in the following section for continuity.

II. Analytical Model for Internal Bending Moment and Springback Prediction

In case of bending of a blank having width to thickness ratio greater than or equal to eight to a bend radius more than three to four times the sheet thickness, it may be assumed that a plane normal section in the sheet remains plane and normal and converge on the center of curvature [24]. It is also considered that the principal direction of forces and strain coincides with the radial and circumferential direction so that there is no shear in the radial plane and gradient of stress and strain are zero in circumferential direction. In the simple bending without applied tension and where the radius of bending (R) is more than several times the blank thickness (t), the neutral surface approximately coincides with the middle surface. For bending of initial flat blank into loaded radius (R), based on power law material model i.e. $\sigma = K\varepsilon^n$ and considering isotropy, applied moment per unit width (M) was reported to the form [17];

$$M = 2K'\left(\frac{1}{\rho^n (n+2)\, 2^{n+2}}\right) t^{n+2} \tag{1}$$

Where, ρ is the radius of neutral surface and for plane strain and isotropy K' is equal to $(1.1547)^{(n+1)}$ K

In practice, plates are often cold formed. Cold formed parts suffer from a phenomenon known as springback. To maintain the final part dimensions overcoming the springback, the radius through which the plate is actually bent must be smaller than the required radius. Assuming linear elastic recovery law and plane strain condition, for unit width of the plate, the relation between unloaded radius (R_f) and corresponding loaded radius (or radius of bending) (R) was derived to the form given by (2) from the moment curvature relationship as per (1) [24], [25].

$$\frac{R}{Rf} = 1 - \left[\frac{6K' t^{n-1}}{R^{n-1}(n+2)\, 2^n}\left(\frac{\left(1-\upsilon^2\right)}{E}\right)\right] \tag{2}$$

Where, ν is Poisson's ratio and E is Young's modulus.

Now based on the geometrical relationship reported by (3), springback ratio can be derived to the form given by (4);

$$R\theta = R_f \theta_f \tag{3}$$

$$\frac{\Delta\theta}{\theta} = R\left(\frac{1}{R} - \frac{1}{R_f}\right) \tag{4}$$

Where, θ is angle of bend in loaded condition and θ_f is angle of bend in unloaded condition.

III. Finite Element Modeling

Conducting the FE forming simulation with high accuracy is important to enable the practical use of the results obtained. In order to study the springback phenomena of the five different ferrous materials namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B suitable for the different pressure equipment applications, FE simulations of the air V-bending process is performed. FE model of air V-bending process was defined in Hyperform v7.0 and solved in LS-DYNA970. The dynamic explicit procedure was used to simulate forming process, and then ".dynain" file was used for springback simulations using static implicit scheme. Geometrical set-up, process parameters, material models and FE parameters used for the presented analysis are discussed in foregoing sections.

A. *Model Geometry*

Fig. 1 shows the geometrical model of air V-bending used for the FE analysis. Based on observed planner symmetry (in XZ plane or Y plane) in case of air V-bending and assumption of plane strain condition (width to the thickness ratio greater than 8), air V-bending process was modeled in two dimensions (2D) with symmetric boundary conditions along the width of the blank. For the presented cases, blank of dimension 150 mm x 6 mm (length x thickness) were selected to study the springback phenomena of the five different ferrous materials namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B. For all cases, die gap (w_d), punch radius (R_p) and die radius (R_d) were set as 50 mm, 5 mm and 5 mm respectively.

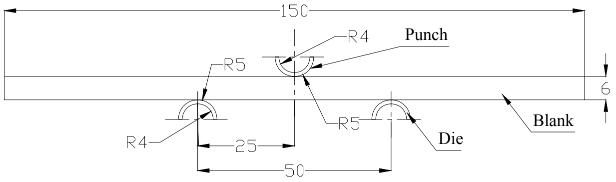

Fig. 1 Geometrical model air V-bending process

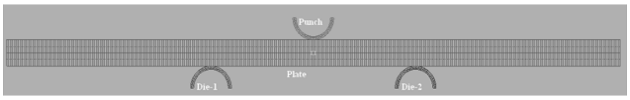

Fig. 2 2D Finite element model

B. *Meshing*

Each part of the air V-bending assembly (i.e. punch, dies, blank) was meshed separately in Hyperform 7.0. Mapped mesh with four nodded quadrilateral fully integrated shell element (QUAD4, TYPE16) was used for FE modeling of blank [26]. The blank of 6 mm thickness were meshed with 300 elements (with approximate element size of 0.5 mm) in length. Whereas, 2 elements were kept in thickness direction so, element size is 3 mm for blank having 6 mm thickness. The die and punch were meshed with 20 elements on 2 circular edges and 2 elements on 2 straight edges. Punch and die set was defined as a rigid body. Fig. 2 shows the 2D FE model used for the analysis.

C. *Material Property*

Table I shows the mechanical properties of five different grades of ferrous materials used for the presented study namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B, suitable for the construction of pressure equipments for different applications [1]. Strength coefficient (K) and strain hardening exponents (n) reported in Table I are calculated based on stress at ultimate point [2]. Material model selected is POWER_LAW_PLASTICITY [26].

D. *Tool Motion*

Displacement loading condition is applied with the total punch travel of 30 mm at velocity of 9 mm/sec [13].

E. *Contact Definition*

Contact interface between punch and blank and die and blank are defined by contact option FORMING_ONE_WAY_SURFACE_TO_SURFACE with friction coefficient of 0.1 at punch-blank and die-blank interfaces [13], [26]. Punch and die set is constrained in rotations about all three principal axes. Die set translations in all three principal axes are constrained where as, punch is assigned translation degree of freedom in z axis direction (i.e. in the direction of punch movement) to apply the load.

F. *Control Cards*

Control cards activation is required to set the solver specific data. Different control cards such as; keywords, hourglass, control shell, control termination, control contacts, control time-steps, database binary extent, database d3plot, database options, etc. are used for analysis. Control cards selection and their parameter values depend on mechanics of the problem, FE modeling and outputs required [26].

IV. RESULTS AND DISCUSSION

A. *Validation of the 2D FE Analysis Procedure with the Published Literature*

Satorres (2005) [13] reported three dimensional (3D) FE analysis of air V-bending for ultra high strength steel material in Ansys LS-DYNA environment. Experimental stress strain curve for 3 mm and 6 mm thick sheet of ultra high strength steel material with material model 24 (MAT_PIECEWISE_LINEAR_ PLASTICITY) [26] was given as an input in the reported analysis by Satorres (2005) [13]. Blank dimensions of 300 mm x 300 mm (length x width) with two different die gaps of 50 mm and 76 mm were selected for 3 mm and 6 mm thick blanks respectively. For 3 mm and 6 mm thick blanks, die radius (R_d) selected was 5 mm and 7 mm respectively. Punch radius (R_p) of 5 mm was selected for all the cases. Blank was mapped mesh with eight nodded brick elements with 90 elements in width and length and two elements in thickness direction. All tools were defined as a rigid body and mapped meshed using shell element QUAD4 with 20 elements at all four edges. Satorres (2005) [13] considered displacement loading condition with punch velocity of 19.5 mm/sec which is double than the actual velocity of 9.5 mm/sec used during experimentation. Contact interface between punch and blank and die and blank were defined by contact option FORMING_ ONE_ WAY_ SURFACE_ TO_ SURFACE [26] with friction coefficient of 0.4 at punch-blank and 0.2 die-blank interfaces [13]. Punch and die set was constrained in rotations about all three principal axes. Die set translations in all three principal axes were constrained where as, punch was assign translation degree of freedom in z axis direction (i.e. in the direction of punch movement) to apply the load. Satorres (2005) [13] showed validation of the FE analysis by comparing experimental stress-strain curve of ultra high strength steel material used as an input with that obtained using FE analysis. Similar analysis was reported by Gajjar et al. (2007) [27] in Hyperform-LS-DYNA environment.

Based on the planer symmetry observed in air V-bending and assumption of plane strain condition, geometry of air V-bending reported by Satorres (2005) [13] was modeled in 2D by Gajjar et al. (2007) [27]. Mapped mesh with four nodded fully integrated quadrilateral shell element (QUAD4, TYPE16) was used for the FE modeling of blank. All the tools were defined as a rigid body. Material model, tool motion, contact definitions were kept same as that used by Satorres (2005) [13] for the validation of the 2D FE analysis. Table III and IV shows the comparison of the stress and plastic strain results obtained using 2D FE methodology used for the present work with 3D FE results reported by Satorres (2005) [13] and Gajjar et al. (2007) [27]. Results of stress and plastic strain obtained using 2D FE analysis are found to be in reasonable agreement with reported results and hence 2D FE analysis as reported in section III was used for the FE springback simulations of the five different ferrous materials under consideration. Now, based on the 2D FE analysis, results on sensitivity of sprinback to various material property parameters are reported in following sections.

B. Effect of yield strength (σ_y) on springback

Fig. 3 shows the effect of yield strength (σ_y) on springback angle. For all the ferrous materials under consideration, though combinations of strain hardening exponent (n) and strength coefficient (K) was observed to be different, springback angle was observed to be increasing with the increase in yield strength (σ_y). Based on Table I and II, ferrous materials SA-36 and SA-515 grade 70 are classified as high ductility steels, SA-299 and SA-612 are classified as high strength steels and SA-724 grade B is classified as extra high strength steels. If Young's modulus (E) is assumed to be same for all the ferrous materials under consideration then with the increase in the flow stress, elastic region becomes larger and larger and springback increases. An observed phenomenon is in line with the results reported by Date et al. (1999) [9].

C. Effect of strength coefficient (K) on springback

Fig. 4 shows effect of strength coefficient (K) on springback angle. For all the ferrous materials under consideration, though combinations of yield strength (σ_y), strain hardening exponent (n) and strength coefficient (K) was observed to be different, springback angle was observed to be increasing with the increase in strength coefficient (K). Increase in the value of strength coefficient (K) leads to increase in flow stress and hence bending moment and results into increased springback. Value of strength coefficient (K) depends on microstructure and processing conditions. So for the same material, variation in strength coefficient (K) greatly affects springback, even if strain hardening exponent (n) remains constant.

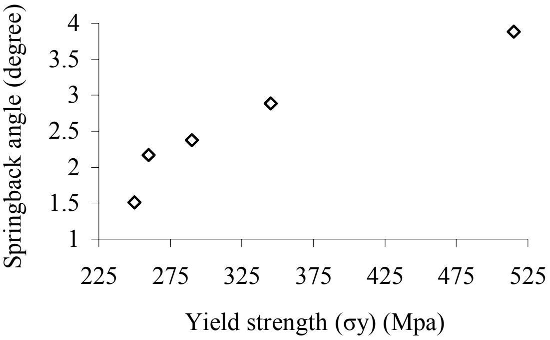

Fig. 3 Effect of yield strength (σ_y) on springback angle

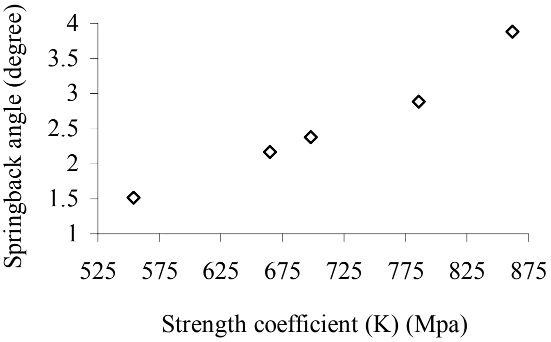

Fig. 4 Effect of strength coefficient (K) on springback angle

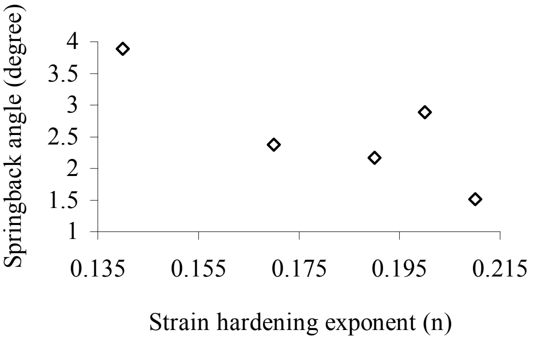

Fig. 5 Effect of strain hardening exponent (n) on springback angle

TABLE III

COMPARISON OF 2D FE STRESS RESULTS WITH PUBLISHED LITERATURE

t (mm)	3D FE analysis stress (MPa) [13]	3D FE analysis results [27]		2D FE analysis results [27]	
		Stress (MPa)	% Error	Stress (MPa)	% Error
*3	1353	1330.7	1.69	1196	12.9
#6	1282	1276.3	0.4	1176	8.26

*For 3 mm thick material, stress values are compared at time 0.468 seconds.
#For 6 mm thick material, stress values are compared at time 0.24 seconds.

TABLE IV

COMPARISON OF 2D FE PLASTIC STRAIN RESULTS WITH PUBLISHED LITERATURE

t (mm)	3D FE analysis plastic strain [13]	3D FE analysis [27]		2D FE analysis [27]	
		Plastic strain	% Error	Plastic strain	% Error
*3	0.145	0.153	-5.51	0.155	-6.4
#6	0.151	0.1529	-1.25	0.156	-3.31

*For 3 mm thick material, strain values are compared at time 0.755 seconds.
#For 6 mm thick material, stress values are compared at time 0.544 seconds.

D. Effect of strain hardening exponent (n) on spingback

Fig. 5 shows the effect of strain hardening exponent (n) on springback. Reported literature shows that, for the constant value of strength coefficient (K) and yield strength (σ_y), lower value of strain hardening exponent (n) results into increased springback [9]. Because, for constant value of strength coefficient (K) and yield strength (σ_y), reduction in strain hardening exponent (n) increases flow stress and hence higher bending moment and springback. For the presented cases of five different ferrous materials under consideration, discussed phenomena is found to be deviating. Maximum springback angle was observed for the ferrous material SA-724 grade B, as strain hardening exponent (n) is minimum and strength coefficient (K) and yield strength (σ_y) is maximum for this material. Because, low strain hardening exponent (n) with high strength coefficient (K) and yield strength (σ_y) results into highest flow stress and correspondingly highest bending moment. From Fig. 5, it can be observed that, for ferrous material SA-612, though value of strain hardening exponent (n) is higher than that for ferrous material SA-299 and SA-515 grade 70, springback angle is observed to be higher. This shows that combination of strain hardening exponent (n), strength coefficient (K) and yield strength (σ_y) controls the springback. Even with further investigation, it can be shown that springback is more sensitive to strength coefficient (K) and yield strength (σ_y) in comparison to strain hardening exponent (n).

E. Effect of layer of high ductility ferrous steel on springback of extra high strength steel

As an alternative to the materials development, hypothetical high strength layered ferrous material with constituents SA-36 and SA-724 grade B is considered to study the effect of layer of high ductility ferrous steel (i.e. SA-36) on springback of extra high strength steel (i.e. SA-724 grade B). Over all thickness of layered ferrous material is taken as 6 mm with 1 mm and 5 mm thickness of the constituents SA-36 and SA-724 grade B respectively. Looking to the difficulty in FE modeling of layered materials, analytical model reported by Gandhi and Raval (2008) [17] as discussed in section 2 is used for the prediction of internal bending moment and springback. Internal bending moment of the layered material is calculated assuming superimposition of the internal bending moment of its constituents. Table V shows the analytical springback for bending of three different ferrous materials SA-36, SA-724 grade B and hypothetical layered material of 6 mm thickness to the loaded bending radius of 100. In 6 mm thick blank of SA-724 grade B, replacement of 16.66 % thickness with SA-36 results into 65.2 % reduction in the springback.

TABLE V
ANALYTICAL SPRINGBACK

Material	Loaded radius (R) (mm)	Unloaded radius (R_f) (mm)	Springback radius	Percentage springback
SA-36	100	107.3	7.3	7.3
SA-724 grade B	100	116.1	16.1	16.1
*Hypothetical layered material	100	110.5	10.5	10.5

* Over all thickness 6 mm with 1 mm and 5 mm thickness of the constituents SA-36 and SA-724 grade B respectively

V. CONCLUSION

Based on the 2D FE springback simulations of five different ferrous materials namely SA-36, SA-299, SA-515 grade 70, SA-612 and SA-724 grade B as per ASME section II part A, following important conclusions are derived;

- High value of strength coefficient and yield strength with low value of strain hardening exponent which is observed in extra high strength and ultra high strength steel materials results into extremely high springback.

- For materials with constant Young's modulus, springback increases with; (i) increase in strength coefficient, (ii) increase in yield strength and (iii) reduction in strain hardening exponent. However, combination of all these material property parameters plays and important role in controlling the springback.
- In comparison to strain hardening exponent, springback is more sensitive to strength coefficient and yield strength of the material.

Based on the analytical springback simulations, it is concluded that as an alternative to the materials development, layer of the high ductility ferrous steel can be used for suppressing the springback during forming of high strength or extra high strength ferrous materials. However, effect of high ductility ferrous material layering on the high strength material's strength and formability needs to be investigated.

ACKNOWLEDGMENT

Reported work is the part of research project funded by Department of Science and Technology, Ministry of Science and Technology, Government of India under SERC-Engineering Science Scheme, sanction letter no. SR/S3/MERC-0026/2007. Authors acknowledge and appreciate the financial support provided by Department of Science and Technology, Ministry of Science and Technology, Government of India.

REFERENCES

[1] ASME Ferrous material specification, Section II Part A and D, 2004
[2] G. E. Dieter, Mechanical behavior of materials under tension, Mechanical Metallurgy. New York, USA: Mc-Graw Hill, 2nd Edition, 1976, pp. 329-348
[3] A. M. Hall, Introduction to today's ultrahigh-strength structural steels. Issued under the auspices of American Society for Testing and Materials and the defense metal information center, 1971
[4] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, 2001
[5] M. Sensuri, J. Cao, A. P. Karafillis and M. C. Boyce, "Accommodation of springback in channel forming using active binder force control: Numerical simulations and experiments," ASME Trans. J. Eng. Mater. Technol., vol. 118, pp. 426-435, 1996.
[6] R. Ruffini and J. Cao, "Using neural for springback minimization in channel forming process," J. Mater. Manuf., vol. 107, pp. 65-73, 1998.
[7] J. Cao J., B. Kinsey and S. A. Solla, "Consistent and minimal springback using stepped binder force trajectory and neural network control," ASME Trans. J. Eng. Mater. Technol., vol. 22, pp. 65-73, 1998.
[8] C. To Wang, G. Kinzel and T. Altan, "Mathematical modeling of plane-strain bending of sheets and plates," J. Mater Process Technol., vol. 39, pp. 279-304, 1993.
[9] P. P. Date, K. Narasimhan, S. K. Maiti and U. P. Singh, "On the prediction of spring back in Vee bending of metallic sheets under plane strain condition," In Proc. Sheet Metal, September 1999, pp. 447-456.
[10] L. J. de Vin, "Curvature prediction in air bending of metal sheet," J. Mater. Process Technol., vol 100, pp. 257-261, 2000.
[11] Jenn-Terng Gau and Gary L. Kinzel, "An experimental investigation of the influence of the bauschinger effect on springback predictions," J. Mater. Process Technol., vol. 108, pp. 369-375, 2001.
[12] G. Carlos, O. Onipede and M. Lovell, "Investigation of springback in high strength anisotropic steels," J. Mater. Process Technol., vol. 159, pp. 91-98, 2005.
[13] Albert Satorres, Bending simulation of High strength steel by finite elements, Master's thesis, University of Oulu, 2005 (may be available at: http://www.oulu.fi/elme/ELME2/PDF/Diplomityot/Masters_Thesis_Albert_Satorres%20.pdf)
[14] R. K. Verma and A. Haldar, "Effect of normal anisotropy on springback," J. Mater. Process. Technol., vol. 190, no. 1-3, pp. 300-304, 2007.
[15] Hyunok Kim, Ninad Nargundkar and Taylan Altan, "Prediction of bend allowance and springback in air bending," ASME Trans. J. Manuf. Sci. Eng., vol. 129, pp. 342-351, 2007.
[16] A. H. Gandhi and H. K. Raval, "Analytical modeling of top roller position for multiple pass (3-Roller) cylindrical forming of plates," In proc. of International Mechanical Engineering Congress and Exposition, Chicago, IL, USA, November 5-10 2006, Paper no. IMECE2006-14279.
[17] A. H. Gandhi and H. K. Raval, "Analytical and empirical modeling of top roller position for 3-roller cylindrical bending of plates and its experimental verification," J. Mater. Process Technol., vol. 197, no. 1-3, pp. 268-278, 2008.
[18] H. Verguts and R. Sowerby, "The pure plastic bending of laminated sheet metals," Int. J. Mech. Sci., vol. 17, pp. 31-51, 1975.
[19] S. A. Majlessi and P. Dadras, "Pure plastic bending of sheet laminates under plane strain condition," Int. J. Mech. Sci., vol. 25, no. 1, pp. 1-14, 1983.
[20] Jang-Kyo Kim and Tong-Xi Yu, "Forming and failure behavior of coated, laminated and sandwiched sheet metals: a review," J. Mater. Process Technol., vol. 63, pp. 33-42, 1997.
[21] R. Hino, Y. Goto and F. Yoshida, "Springback of sheet metal laminates in draw bending," J. Mater. Process Technol., vol. 139, pp. 341-347, 2003.
[22] K. Yilamu, R. Hino, H. Hamasaki and F. Yoshida, "Air bending and springback of stainless steel clad aluminum sheet," J. Mater. Process. Technol., vol. 210, no. 2, pp. 272-278, 2010.
[23] O. Tetsuo, T. Nicolas, K. Seiichiro, Y. Jun and K. Toshihiko, "Experimental and numerical analysis of multilayered steel sheets upon bending," J Mater. Process. Technol., doi:10.1016/j.jmatprotec.2010.07.003, To be published.
[24] Z. Marciniak, J. L. Duncan, Mechanics of sheet metal forming, Edward Arnold Ltd., London, 1992.
[25] Edward M. Mielnik, Metal Working Science and Engineering, New York, USA, McGraw Hill Book Co., 1991.
[26] LS-DYNA Keyword Users Manual, Version 970, Livermore Software Technology Corporation (LSTC), April 2003.
[27] H. V. Gajjar, A. H. Gandhi and H. K. Raval, "Finite Element Analysis of Sheet Metal Air-bending Using Hyperform LS-DYNA," Int. J. Mech. Sys. Sci. Eng., vol. 1, no. 2, pp. 117-122, 2008.