Trans Indian Inst Met (2020) 73(2):285–300
https://doi.org/10.1007/s12666-019-01843-5

TECHNICAL PAPER

Experimental Analysis and Prediction of Springback in V-bending Process of High-Tensile Strength Steels

Muhammad Wasif[1] · Syed Amir Iqbal[1] · Muhammad Tufail[2] · Hassan Karim[1]

Received: 17 July 2019 / Accepted: 5 November 2019 / Published online: 16 November 2019

Abstract Experimental setup has been designed, to study the effects of thickness, width, bend angle and machine tool parameters on the springback, in two high-tensile strength steel grades, namely JSC440 and JSC590, during the V-bending process. Relationship between the springback and the parameters are analyzed using plots. Optimal combination of parameters for the minimum springback is evaluated. Analysis of variance has been carried out to analyze the magnitude of influence of these parameters on the springback. Using the experimental results, analytical models for the prediction of springback for the combinations of blank thickness, width, bend angle and machine tool parameters have been developed. Results reveal that in V-bending of JSC440, thickness and width are the dominant factors influencing the springback, whereas in JSC590 steel, insignificant change in springback is observed with the change in width of blank and using the hydraulic press with holding. However, thickness of steel sheet and bend angle influence significantly the springback in JSC590 steels.

✉ Muhammad Wasif
mwasif80@gmail.com

Syed Amir Iqbal
samir@neduet.edu.pk

Muhammad Tufail
pvc@neduet.edu.pk

Hassan Karim
h.karim@live.com

[1] Department of Industrial and Manufacturing Engineering (IMD), NED University of Engineering and Technology, Karachi, Pakistan

[2] NED University of Engineering and Technology, Karachi, Pakistan

Keywords High tensile strength · Sheet-metals · V-bending · Springback · JSC440 · JSC590

1 Introduction

Sheet-metals are the form of cold- or hot-rolled metals having very high length-to-thickness ratio [1]. Sheet-metals parts are bent, formed, drawn or fabricated for different kinds of machines, automobiles, household equipments, aircrafts, electronic devices, etc. These sheet-metal parts have become essential requirements in every household or commercial equipment. High-tensile strenght cold- and hot-rolled sheet-metals are used by all automobile original equipment manufacturers (OEMs), mainly in the structural parts due to the higher strength-to-weight ratio and appropriate toughness in the structure for the safety and fuel efficiency.

Sheet-metals parts are produced through bending, forming, drawing, piercing and several other processes. Sheet-metal bending is one of the most applied manufacturing processes [1].

Bending of sheet-metals is the plastic deformation of the blank, making a permanent change and forming a bend in a straight sheet. There are four basic types of sheet-metals bending processes, which include V-bending, rotary bending, edge bending and air bending [1]. In V-bending, v-shaped concave die and the convex punch are used (Fig. 1).

In V-bending process, sheet-metals can be bent to both acute and obtuse angles, including bending accurately to 90°. In V-bending process, load is applied through the punch to a sheet-metals blank, which is plastically deformed to acquire the shape of gap between the die and

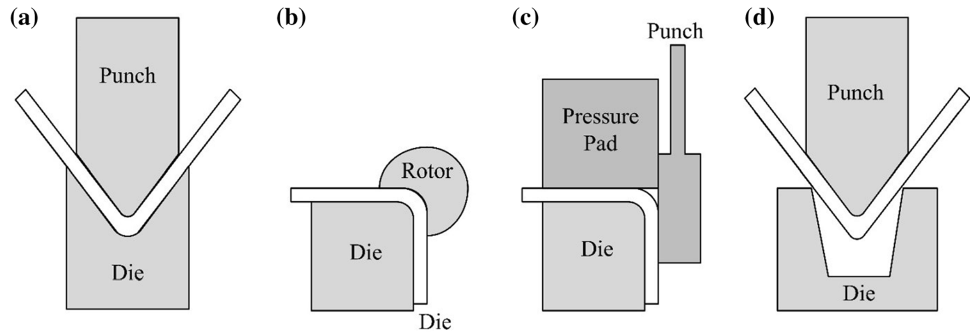


Fig. 1 Sheet-metal bending processes: **a** V-bending, **b** rotary bending, **c** edge bending, **d** air bending

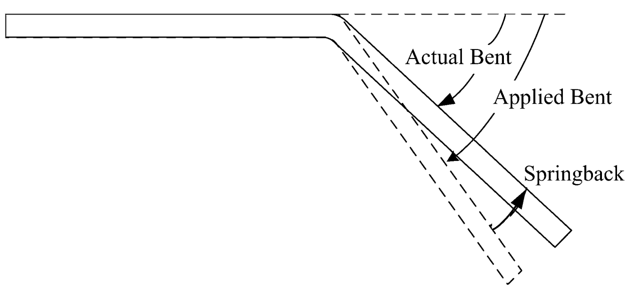


Fig. 2 Springback in sheet-metals bending

punch. It has been observed that when the load is released, the sheet-metals tends to recover due to the elastic recovery of the material. This elastic recovery called *springback* [2] is shown in Fig. 2. Springback can either be negative or positive in nature and depends upon the tensile strength of the material [2].

Few important factors influencing the springback are: the mechanical properties of sheet-metals, thickness of sheet, width over which the bend is formed, radius of bend, bend angle, types of machine tool, stroke capabilities, tooling and specific metal bending arrangement [1, 2].

In high-tensile strength sheet-metals, negative springback are observed widely [1, 2] and hence are experimentally proved in this research. The results of analytical models are also compared with the experimental results, which proves that the analytical models does not predict the negative springback in the high-tensile strength sheet-metals.

To address the springback and its effects during the mass production in V-bending process, an extensive literature review has been conducted.

Cardena et al. developed the relationship between the springbacks of steel and aluminum alloys based on the data gathered through the experimental setups [3]. They concluded that the springback can be reduced as the tensile stress reaches toward the yield stress. In another research, Tekiner analyzed the effect of springback on different high-tensile strenght sheet-metals using different thicknesses of workpieces on modular dies in the air bending process [4]. Fei and Hodgson showed that the effect of change in Young's modulus during the plastic deformation and the coefficient of friction play an important role in the springback in TIRP steel [5]. Dong-juan et al. developed an analytical model for the springback in V-bending process, which is based on Hill's yielding criterion and plane strain condition. Effects of contact pressure, length of bending arm between the punch and die, transverse stress, neutral surface shifting and sheet thickness thinning on the sheet springback of V-bending are considered [6]. Ozturk et al. performed experimental analysis, to study the effects of springback on dual-phase (DP) steels, by varying the rolling directions of the steel sheets and temperature [7]. Inamdara et al. experimentally gathered the data on the air V-bending of different materials and carried out the analysis of variance (ANOVA) to study the behavior of springback on the geometry of the tools, workpiece and properties of those materials [8]. Ramezani et al. modeled the kinetic friction of V-bending process of ultra-high-tensile strength steels in finite element modeling (FEM) and studied the springback, based on the pressing speed, over forming and holding time of workpiece in the press [9]. Swiatoniowski and Balon presented a model to determine the optimized workpiece and correction of deviations in the workpiece due to the springback in the sheet-metals parts [10]. Slota and Jurcisin studied the behavior of steels TRIP, AHSS and mild steel using the FEM method and developed a prediction model of the springback on those material for the air bending process [11]. Da Silva et al. compared the springback in an advanced high-tensile strength material with the existing high-tensile strength materials [12]. Yang et al. worked on the prediction of springback in DP780 (advanced high-tensile strenght steel) during the air bending process, which is quite difficult to predict, due to varying Young's moduli during the stress application [13]. Jung et al. studied the anisotropy in dual-phase steel (advanced high-tensile strenght steels) and developed a model to predict the springback during the U-bending process. The model is also validated using several experiments [14]. Choi et al. worked on experimental and FEM-based simulation of double- and single-stage U-bending of high-tensile strenght steel. They observed the non-proportional effect of loading on the springback [15].

Leu and Zhuang developed a predication model for the springback in high-tensile strenght material, based on numerical simulation methods. The model mainly considers the parameters: punch radius, material strength and sheet thickness [16]. Cai et al. presented an experimental research to study the springback in high-tensile strenght aluminum alloy (AA6082) during the U-bending process, varying the elevated temperature. It is observed that the springback is reduced at the high elevated temperature during the U-bending process [17].

Nakagawa et al. studied the effect of springback on ultra-high-strength steel thin sheets during the stamping and its subsequent quenching process. He applied several techniques to reduce the springback by using the holding technique during the stamping process [18]. Noma et al. performed finite element modeling (FEM)-based investigation of springback in sheet-metals by incorporating strength differential (SD) model developed by the experiments [19]. Liu et al. proposed a unique springback FEM model and analyzed the springback in stiffed panel during the milling process of the panel layer by layer. These researchers also validated the FEM model using the milling experiment [20]. Liu et al. proposed a research on FEM analysis of springback on titanium square tubes; researchers also experimentally validated the results. It has been analyzed that the springback increases with the radius of bent of the tube [21]. Ramadass et al. performed another FEM analysis to optimize the springback in Ti Grade 2 sheets. In this research, Taguchi orthogonal array has been applied and spring-to-noise ratio is used to optimize the input parameters for the minimum springback in the sheet-metals [22]. Lin et al. also proposed a FEM and experimental validation model for the springback in U-channel specimen of MP980 and AA6022-T4. It is confirmed from the research that yield criteria consideration in modeling improves the accuracy of springback prediction in FEM models [23].

In the literature review, the effects of springback on different sheet-metal materials have been addressed. Analytical, experimental, numerical and FEM models are developed which are specific and based on independent variables such as sheet-metal materials, initial geometry of workpiece, tool and die geometry, process parameters, lubrication, initial temperature, speed of operations and type of bending process.

2 Methodology

It is of high demand in the industry to gather the data and analyze the mechanical properties of high-tensile strength steel grades. Therefore, analysis and prediction of springback in high-tensile strength steels have been focused in this research to facilitate the industry in this regard, especially when the available analytical models do not present the true patterns of springback in high-tensile strength steels sheets. In this research, study of springback in the cold-rolled, high-tensile strength materials, namely JSC440 and JSC590 steels, has been conducted.

The chemical compositions of these steel grades are given in Table 1, where major composition such as C, Si, Mn, P and S is mentioned.

In this research, experimental and analytical models for the springback in JSC440 and JSC590 steels have been developed for different blank geometries and machine tool parameters. Factorial design of experimental (DOE) method has been adopted, and a number of experiments have been performed with different workpiece geometries, materials, machine tool parameters and bend angles with the designed set of punch and die. The results of experiments have been plotted to observe the effects on springback due to the changing variables. Analysis on the results has also been conducted, to determine the optimal parameter values with minimum springback. Analysis of variance (ANOVA) has also been carried out to study the dominant factors affecting the springback magnitudes. Finally, analytical models for the prediction of springback for different bend angles and combination of parameters have been developed.

3 Experimental Determination of Springback

Factorial design method is adopted to design the experiments for the analysis of springback. Sets of experiments have been designed, to study the springback in the cold-rolled, high-tensile strength steel sheets (JSC440 and JSC590 steels). To understand the behavior of springback, several input parameters are varied, to confer their effects on the springback. Since there is huge list of input parameters which may affect the springback, a limited number of major input parameters are used in this study. Two types of commercial machine tool presses are used in this experiment, which are selected for the optimal load required to bend the both types of sheet-metals. A mechanical press of 63 tons and a hydraulic press of 75 tons with the applying pressure of 30 kg/cm^2 and 180 kg/cm^2 are selected. According to the factorial design methods for the experiments, varying parameters to study the springback are listed in Table 2. The parameters, which are kept constant, are shown in Table 3.

Experiments are conducted on JSC440 and JSC590 steel strip with varying thicknesses of 1.0 mm, 1.4 mm and 1.6 mm having widths of 20 mm and 50 mm of each. Three different V-bending dies for the 60°, 90° and 120° bend angles, made of mild steel, are designed to perform

Table 1 Chemical composition (wt%) of high-tensile strenght steel sheets (automotive grade)

Grade	C	Si	Mn	P	S	Fe
JSC440	0.17	0.55	0.70	0.03	0.02	98.53
JSC590	0.20	0.50	2.00	0.03	0.03	97.24

Table 3 Constant parameters

Parameters	Value
Blank length	170 mm
Internal bend radius/punch radius	8 mm
External bend radius/die radius	10 mm

the bending operations. These die sets are designed such that they can be fitted in a single die assembly, which can be placed in both mechanical and hydraulic presses. Table 4 shows the experimental design with the replication of the experiments two times for the accuracy of responses.

Using the Minitab software [24], experimental setups with 216 experiments are designed, each of which is replicated for the accuracy of results. The experiments have also been randomized to exclude the chances of biasness. Each blank is bent on the press, and bend samples are measured using a digital bevel protector having 1-min precision. Measured springback samples are gathered, and the data are plotted against the different parameter using the MATLAB [25]. Samples which are bent using the presses are shown in Fig. 3.

4 Analysis of Springback

Springback in the JSC440 steel sheet-metals is plotted against the three thicknesses of the strips used in the experiments and is shown in Figs. 4 and 5. Each type of samples is designated in the legend with the combination of parameters used for the experiments. For example, in Fig. 4, M1 set shows that the blank of width (w) 20 mm is bent to an angle (A) of 60° with the dead-end gap (G) between punch and die equals to the thickness (t) of the sheet-metals strip. Here "M" of sample M1 denotes that the sample is bent using the mechanical press. In Fig. 5, set H2 shows the blank of width (w), 20 mm is bent to an angle (A) of 60° with the hydraulic pressure of (P) 30 kg/cm^2 with a holding time (h_t) of 20 s between the punch and the die. Here "H" of sample H1 shows that the blank is bent using the hydraulic press. Figures 4 and 5 show that both positive and negative types of springback exist in the material. It can be observed in these figures that the springback in JSC440 steel strips is usually negative in nature. It means that when the press force is removed from the strips, it bends inside due to the high residual compressive stresses near the bend radius. It can also be seen from the two figures that the relationship between the thickness of the strips and the springback is not linear in the JSC440 steel. The springback magnitude generally reduces (negative springback to zero) with the increase in thickness of the strip except in few cases. In case of samples M7, M8 and M12, exceptions have been observed, where the springback is increased with the increase in the thickness. In M12, it increases in 1.2 mm thickness. Figure 4 also shows that the impact of reducing gap between the punch and the die to 0.7 times of thickness has minute effect of reduction in springback for the thickness of 1 mm and 1.2 mm and no effect over 1.4 mm (see samples M1 and M2, M3 and M4).

Figure 5 shows the trend in springback, when the blank of JSC440 steel strips is bent using the hydraulic press with varying pressures and holding times. It can be observed that the magnitude of springback usually decreases with the increase in thickness of strips, except in few cases, such as H1, H3, H4 and H16. In most of the cases, negative springback is observed with the low magnitude. There is a minute decrease in springback magnitude, when the blank is hold for 10 s between the punch and the die.

Table 2 Varying parameters

Parameters	Value	
	For mechanical press	For hydraulic press
Load tonnage	63 tons	75 tons with (30 kg/cm^2 and 180 kg/cm^2)
Load holding time	None	0 s, 10 s
Gap between punch and die	Equal to blank thickness (t) Equal to 0.7t	Equal to blank thickness (t)
Blank material	Cold-rolled JSC440 and JSC590 steels	
Thickness of blank (t)	1 mm, 1.2 mm, 1.4 mm	
Width of blank (w)	20 mm, 50 mm	
Bend angle (A)	60°, 90° and 120°	

Table 4 Design of experiment

Parameter	Levels	Description
Material	2	(1) JSC440 steel, (2) JSC590 steel
Machine tool	6	Mechanical press
		hold = 0 s, Load = 60 tons with varying gaps (G) between die and punch (1) $G = t$, (2) $G = 0.7t$,
		Hydraulic press
		Constant gap (G) between die and punch, i.e., $G = t$ with variable time and tonnage, (3) hold = 0 s, (4) hold = 20 s, (5) load = 30 kg/cm^2, (6) load = 180 kg/cm^2
Blank thickness (t)	3	(1) 1.0 mm, (2) 1.2 mm, (3) 1.4 mm
Blank width (w)	2	(1) 20 mm, (2) 50 mm
Bend angle (θ)	3	(1) 60°, (2) 90° and (3) 120°
Number of experiments	216 × 2 = 532 experiments	

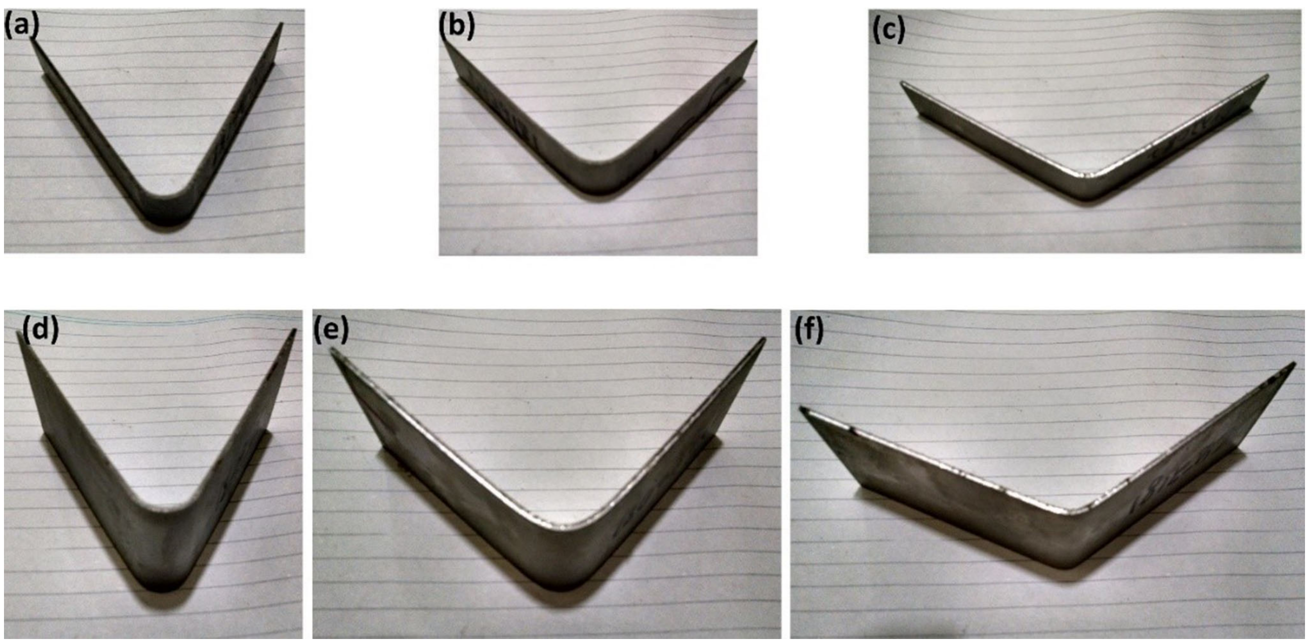


Fig. 3 JSC440 steel sheet-metals samples: **a** sample with 20 mm width bent to 60° ,**b** sample with 20 mm width bent to 90°, **c** sample with 20 mm width bent to 120°, **d** sample with 50 mm width bent to 60°, **e** sample with 50 mm width bent to 90°, **f** sample with 50 mm width bent to 120°

Figures 6 and 7 show the springback in the JSC590 steel blanks of different thicknesses bent using mechanical and hydraulic presses. Unlike the decreasing trend of springback magnitude with the thickness observed in JSC440 steel strips (Figs. 4 and 5), the springback in the JSC590 steel strips do not follow the same pattern in sheet-metals bent using the mechanical press (see Fig. 6) or hydraulic press with different loads (Fig. 7). In most of the cases, it has been observed that the springback is least for the thickness of 1.2 mm of strip, whereas it is maximum for the thickness of 1 mm. Exception to this pattern is observed in case of samples M14, M17, M18 and M23, H27 and H28, where highest springback is observed at the thickness of 1.2 mm (see Figs. 6, 7). Reduced springback magnitude is observed when the JSC590 steel strips are bent using the mechanical press, with a die and punch having a dead-end gap of 0.7 times the thickness. Impact of changing pressure and holding time is observed in case of 1.4 mm sheet-metals, when bent using the hydraulic press, whereas no such impact is observed in JSC590 steel sheet-metals having 1.0 mm and 1.2 mm thicknesses.

Springback in the JSC440 steel strips is plotted against the widths of the strips (Figs. 8, 9, 10). Figure 8 shows the springback versus the width of the strips bent using the

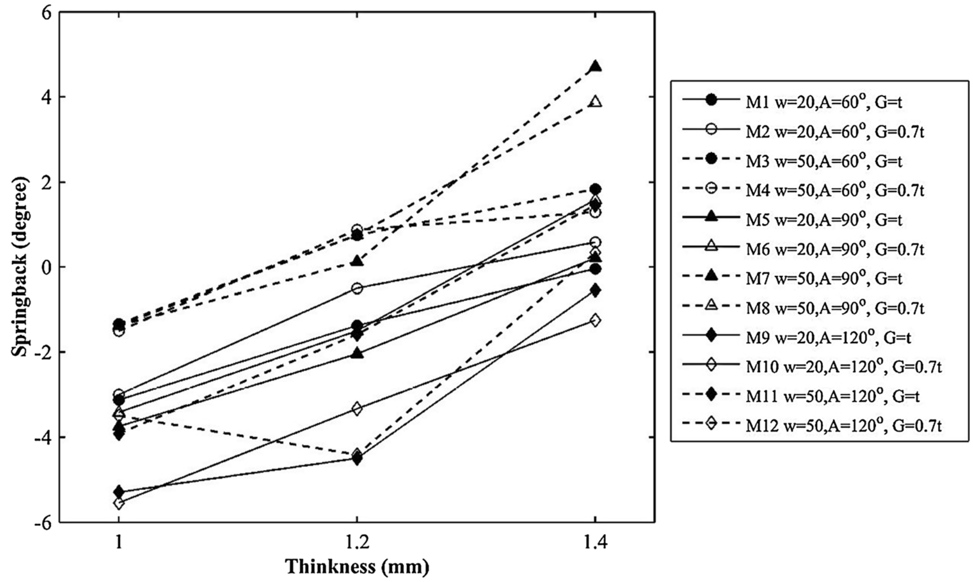


Fig. 4 Thickness versus springback in JSC440 steel sheet-metals bent using the mechanical press

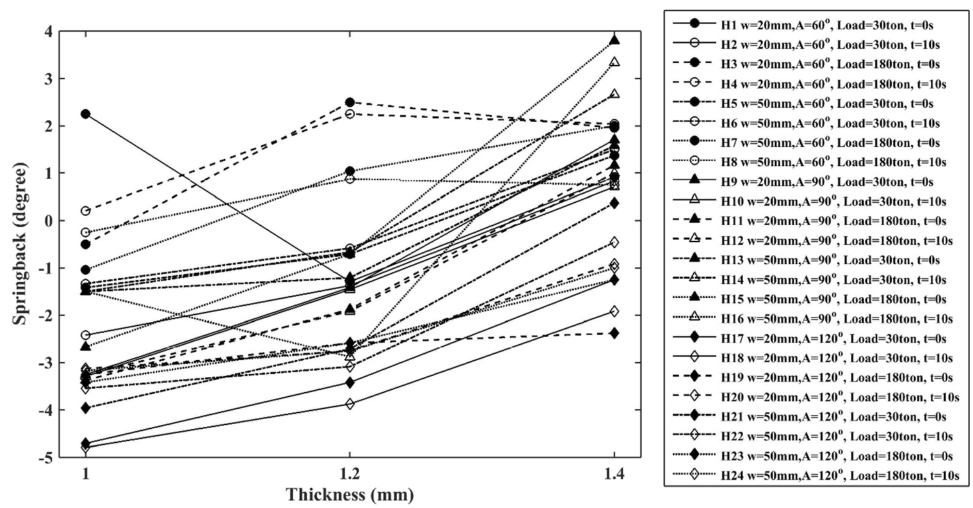


Fig. 5 Thickness versus springback in JSC440 steel sheet-metals bent using the hydraulic press

mechanical press with the different dead-end gap between the punch and the die. It can be clearly seen that the springback magnitude is decreased as the width of the JSC440 steel strip is increased. Exception can be noted in case of M37 to M41, where the thickness of strip is 1.4 mm. Decreasing behavior of springback magnitude with the increase in width is observed, when the JSC440 steel strips are bent using the hydraulic press without holding and with holding for 10 s between punch and the die (shown in Fig. 9). Exception can again be noted in material having higher thickness as well as width in the combination of parameters in H61 to H64. Figures 8 and 9 show that the magnitude of the springback is reduced when the strips are bent using the hydraulic press with the pressure of 30 kg/cm^2 and holding the strip for 10 s. Figures 8 and 9 show that sample M36 has the reverse trend, when the springback is increased, as the width is increased. In sample H49, the springback is changed from positive magnitude to negative. Figure 10 shows that the same material strips bent using the hydraulic press with the pressure 180 kg/cm^2 and varying holding times. Figure shows that in most of the cases, such as H67, H73, H79 and H80 springback magnitude reduces for the higher widths. In few cases (H71, H72, H77 and H78), there is no change in springback is observed with the increase in width. Figures 10 and 11 show that the springback is reduced while bending the strips of JSC440 steel with the hydraulic press of load 30 kg/cm^2 and 180 kg/cm^2 and applying holding time of 10 s.

Figures 11, 12 and 13 show the relationship between the springback and width of the JSC590 steel strips which are bent using the mechanical presses, hydraulic press with 30 kg/cm^2 and hydraulic press with 180 kg/cm^2 loads, respectively. Figure 12 shows that in most of the cases of

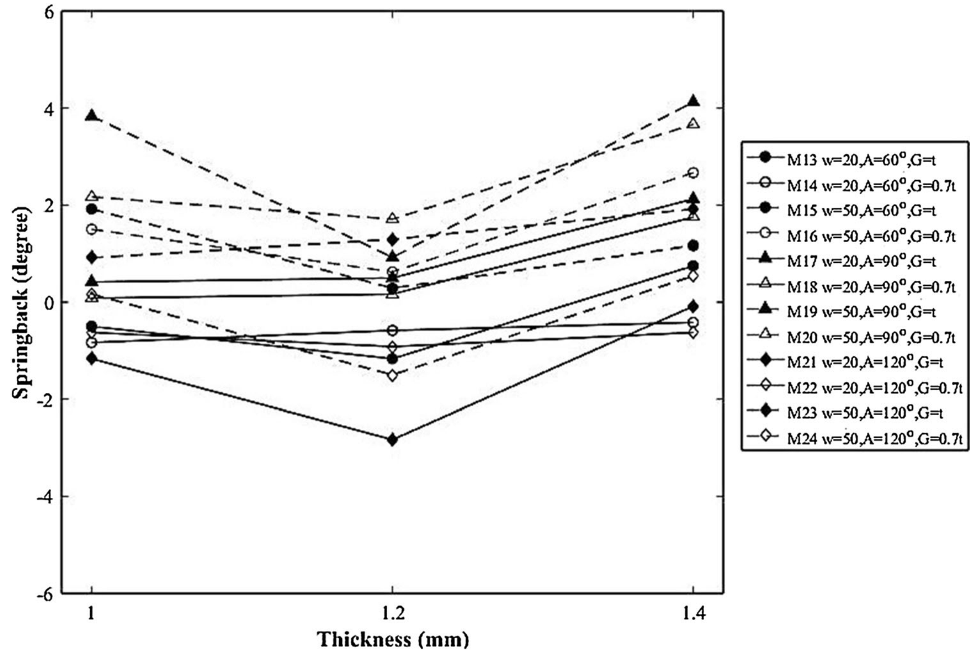


Fig. 6 Thickness versus springback in JSC590 steel sheet-metals bent using the mechanical press

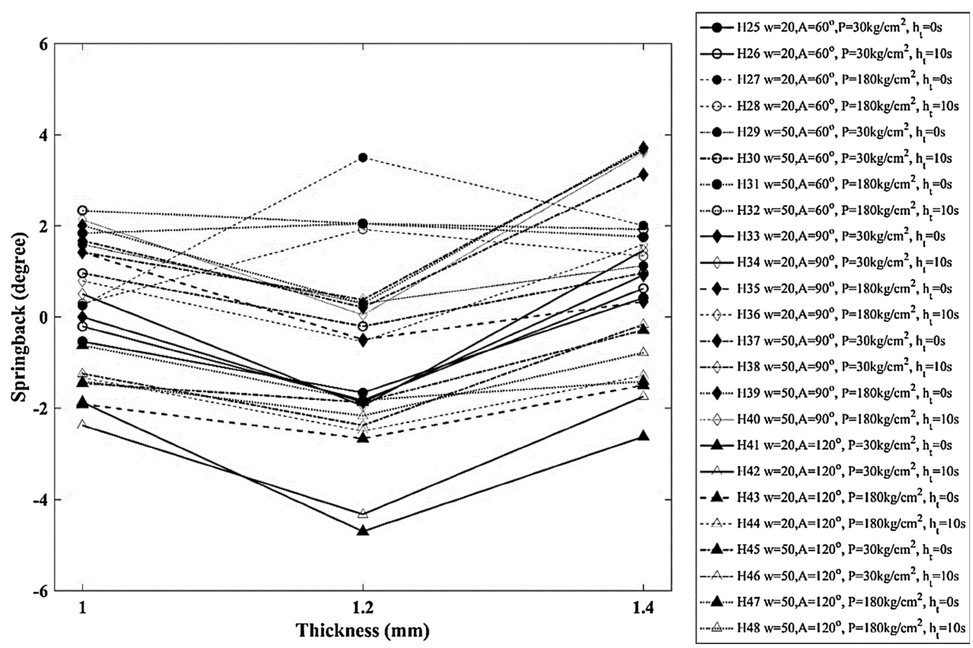


Fig. 7 Thickness versus springback in JSC590 steel sheet-metals bent using the hydraulic press

the sheet-metals strips of thicknesses 1.0 mm and 1.2 mm, the springback magnitude reduces with the increase in width of the strips. M53 is exception of this. In case of strips with 1.4 mm thickness, the springback increases as the width of strip is increased. It can be since the residual stresses in thin sheet-metals are low due to the stress distribution over the width, whereas it is high in the thick strips due to the mode concentration within the width. It can be seen from the figure that the springback is again increased in sheet-metals of thickness 1.4 mm with the increase in width (see Fig. 12). Springback magnitude is observed which is reduced in the JSC590 steel sheet-metals when it is bent using the press load of 180 kg/cm^2 in the hydraulic press. In this figure, springback with respect to the width has lower slope. Lower springback magnitude is shown in Fig. 13 as the width of the strips is increased. It shows that the press load is unable to overcome the residual stresses. Figure 13 shows that positive springback exists in the JSC590 steel sheet-metals when bent to angles of 60° and 90°, whereas negative springbacks are observed when these sheet-metals are bent to 120°. From this figure, it can be inferred that the springback is reduced with the increase in width, whereas

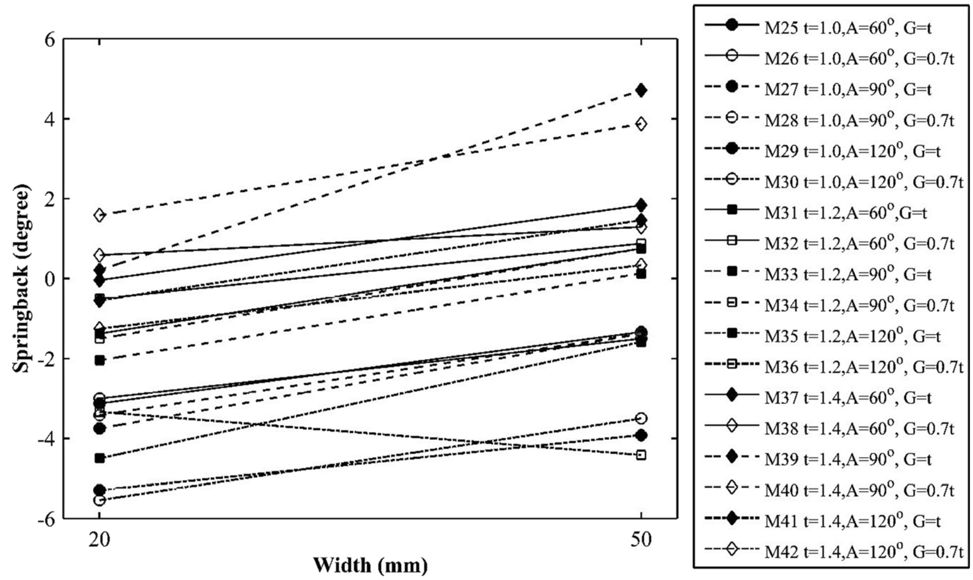


Fig. 8 Width versus springback in JSC440 steel sheet-metals bent using the mechanical press

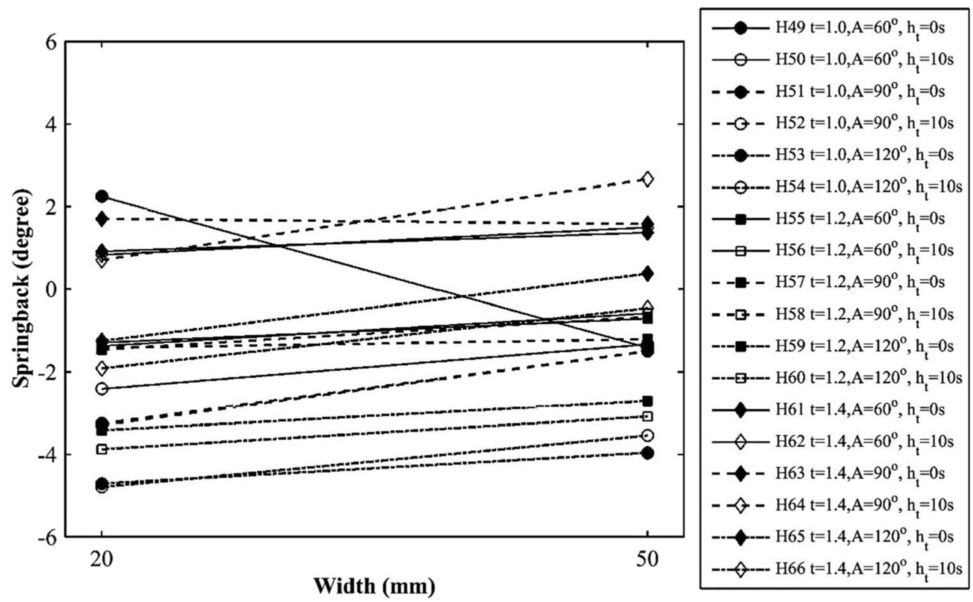


Fig. 9 Width versus springback in JSC440 steel sheet-metals bent using the hydraulic press (30 kg/cm^2)

exceptions are observed in case of combination of parameters: H107, H109, H111, H112 and H119.

Figure 14 shows that the springback increases while bending the JSC440 steel strips to a bend angle of 90° in few cases (M62, M70, M71 and M72). It may be because the strips are bent in the acute angle without any holding, where the tensile stresses increase to cause the positive springback in the material. Figure 15 shows that this trend of higher springback magnitudes at the 90° bends is also present when the sheets are bent using the hydraulic press. Hence, it can be concluded that while bending the JSC440 steel strips with either the mechanical or hydraulic pressures, the springback magnitude (either positive or negative) is higher for the case of 90° bends.

While bending the JSC590 steel metal strips using the mechanical and hydraulic presses, it has been observed that the positive springback magnitude is higher in strips, while bending to acute angles. It can be due to the higher tensile residual stresses causing the bend to be open and causing the positive springback (see Figs. 16, 17). While bending the JSC590 steel strips using the mechanical press (see Fig. 17), it has been observed that the springback magnitude is almost same for the bents of 60° and 120°. Negative springback is observed while bending JSC590 steel strips using the hydraulic press (see Fig. 18). No prominent relationship between the springback and the bent angle is observed also for the JSC590 steel strips.

Fig. 10 Width versus springback in JSC440 steel sheet-metals bent using the hydraulic press (180 kg/cm^2)

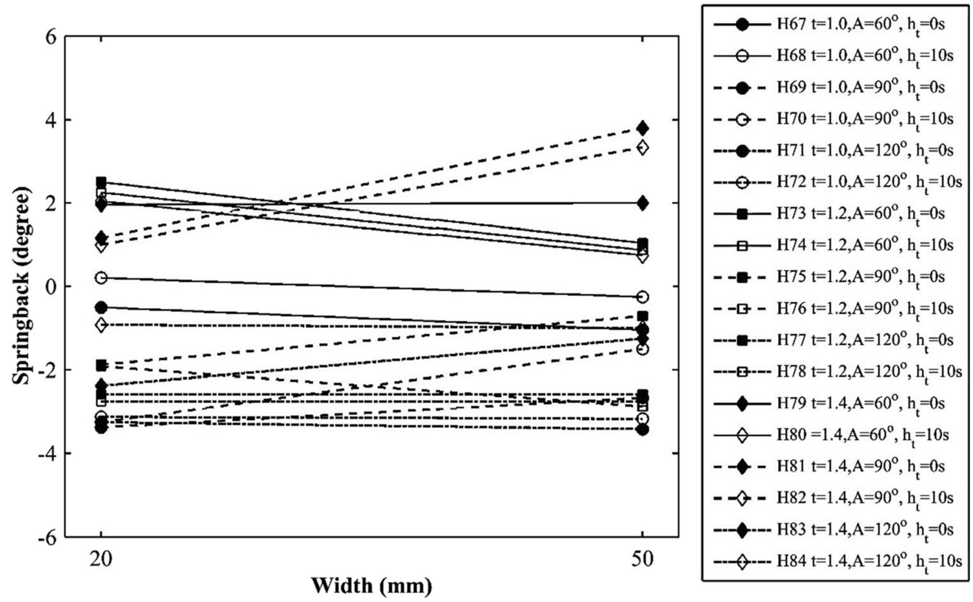
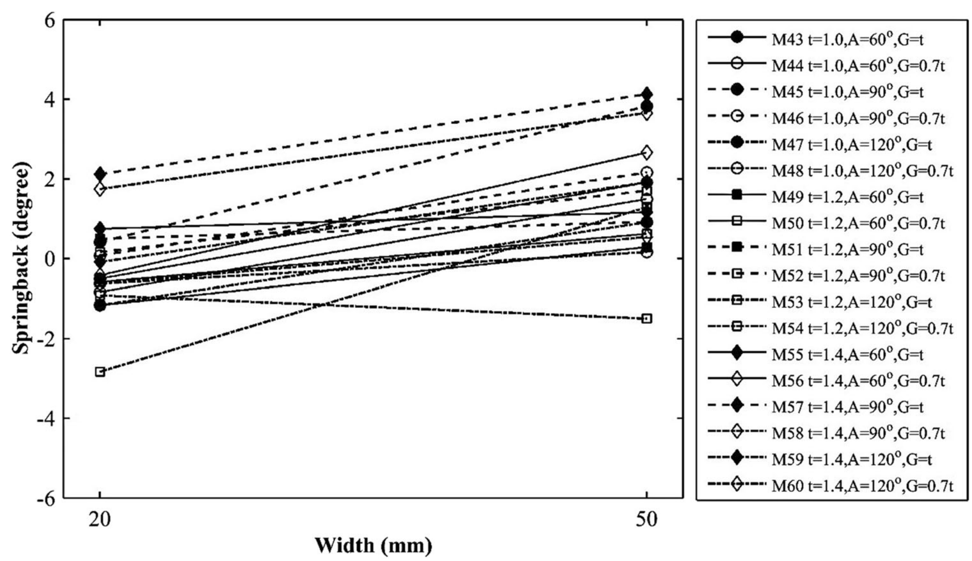


Fig. 11 Width versus springback in JSC590 steel sheet-metals bent using the mechanical press



Analysis of variance (ANOVA) has been carried out on the data obtained through the springback experiments on the JSC440 steel and is presented in Table 5.

In this table, Column "Source" contains the factors and their interactions influencing the springback. "DF" shows the degree of freedom of data provided. "Adj SS" represents the adjusted sum of squares for the data. "Adj MS" is the adjusted mean sum of squares of the data. *F*-value represents the ratio of adjusted sum of squares of the factors or interactions to the adjusted sum of square of the error. For example, *F*-value of width is 24.57, which is the ratio of Adj MS of width 23.22 to the Adj MS of error 0.945. Finally, the *P* value is the probability of *F*-value for the designated degree of freedoms evaluated using the probability data, which is 0.00012 for the width.

P-values less than 0.05 (with the confidence interval of 95%) clearly supports the discussion presented above that the factors like thickness, width, bend angle, interaction of thickness and bend angle have the considerable influence on the springback. Higher *F*-value shows the significance of effect of thickness, width and bend angle on the springback, respectively. Other factors presented in Table 4 are eliminated due to the insignificant influence on the springback in the screening ANOVA.

On experimental data of springback in JSC590 steel, analysis of variance (ANOVA) has been carried out and is presented in Table 6. It supports the discussion mentioned above that the factors have *P*-values less than 0.05 (with the confidence interval of 95%); thickness, width, bend angle and interaction of thickness and initial angle have the

Fig. 12 Width versus springback in JSC590 steel sheet-metals bent using the hydraulic press (30 kg/cm^2)

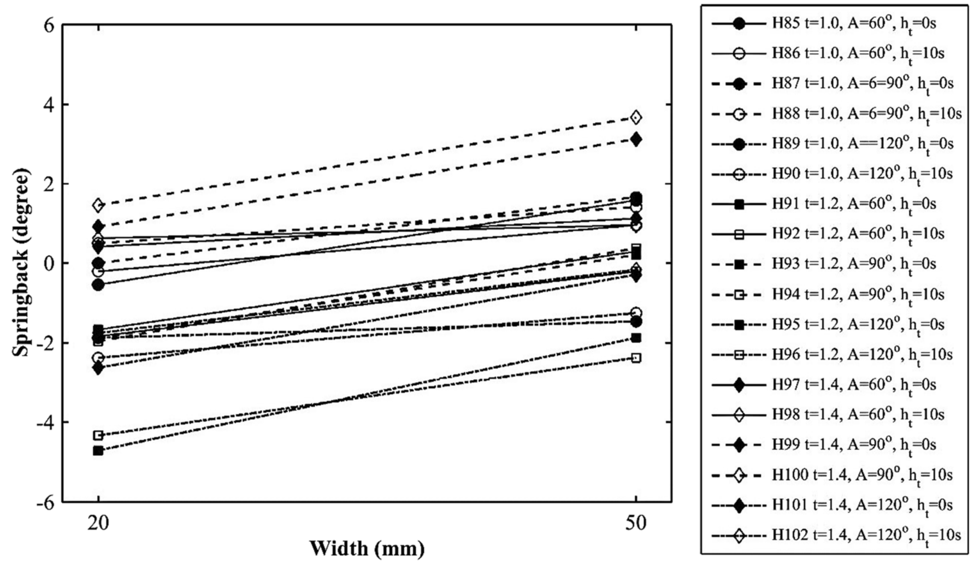
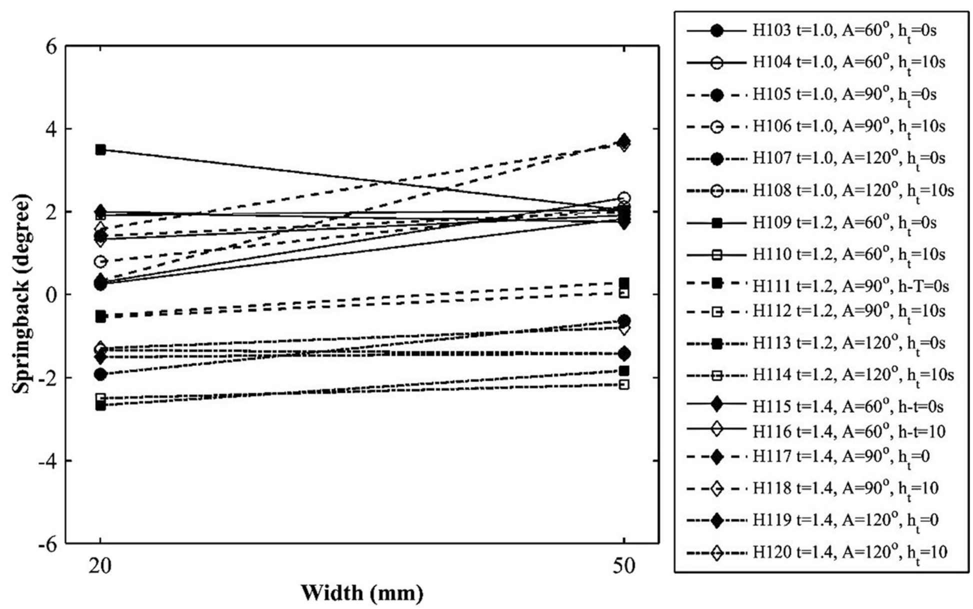


Fig. 13 Width versus springback in JSC590 steel sheet-metal bent using the hydraulic press (180 kg/cm^2)



considerable influence on the springback in JSC590 steel sheets. Higher *F*-value shows the order of effect of bend angle, width and thickness on the springback, respectively. Other factors presented in Table 4 (such as hold time, gap between die and punch) do not have significant effects (*P*-value higher than 0.05) on the springback. Hence, these factors are eliminated in the screening ANOVA.

Tables 7 and 8 show the minimum and maximum springback at the three types of thicknesses of JSC440 steel sheet-metals bent using the mechanical and hydraulic presses, respectively. It shows that the minimum springback for the thickness of 1 mm is observed for the width of 20 mm bent using the hydraulic press with holding time of 10 s (case H4 in Table 8). For the thickness of 1.2 mm, with the width 50 mm, it is found in case of M7 in Table 7. For the thickness of 1.4 mm, it is found for the width of 20 mm bent using the mechanical press (see case M1 in Table 7). Maximum springback is also shown in Tables 7 and 8 for these thicknesses.

It shows that in most of the cases, the springback is minimum while bent between 60° and 90° having the gap between die and punch equal to the thickness of the sheet. Tables 9 and 10 show the minimum and maximum springback at the three types of thicknesses of JSC590 steel sheet-metals bent using the mechanical press and hydraulic presses, respectively. Minimum springback in JSC590 steel of thicknesses 1.0 mm and 1.2 mm are observed while bending using the hydraulic press with holding time of 0 and 10 s, respectively (H33 and H29 in Table 10). Minimum springback in 1.4 mm thickness of JSC590 steel is

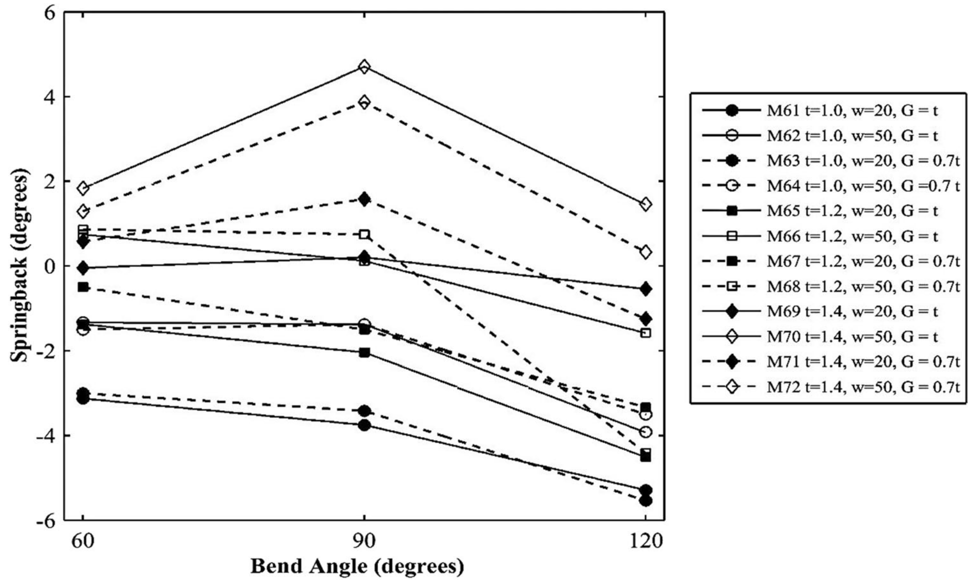


Fig. 14 Bend angle versus springback in JSC440 steel sheet-metals bent using the mechanical press

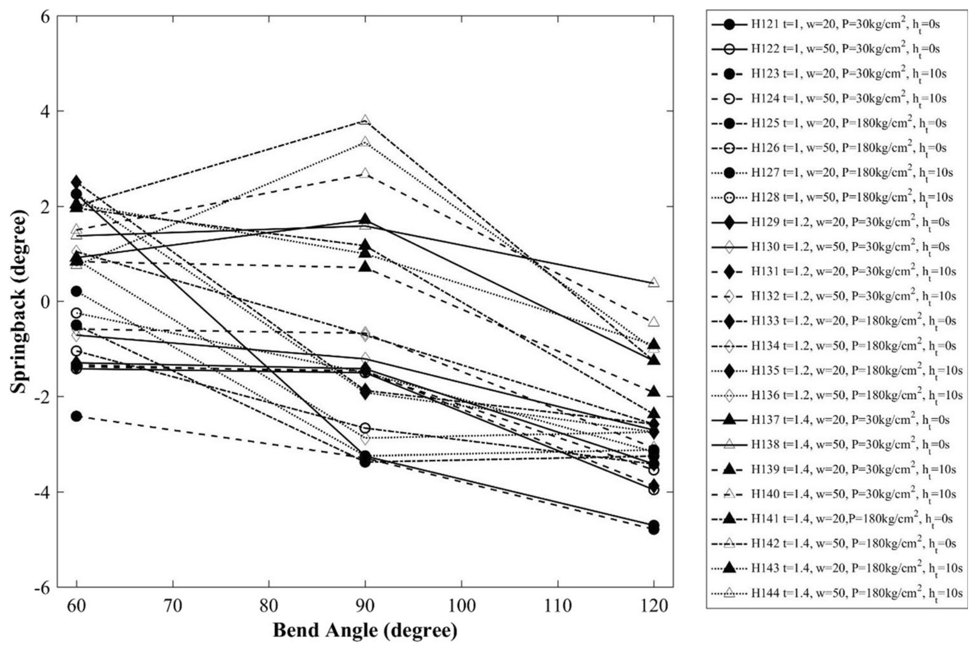


Fig. 15 Bend angle versus springback in JSC440 steel sheet-metals bent using the hydraulic press

observed while bending using the mechanical press (M2 in Table 9).

Using the Minitab software, analysis of variance (ANOVA) has been carried out on the data gathered through the experiments for the JSC440 and JSC 590 steels. Absolute springback has been taken as the dependent variable. It has been observed from the *P*-values of the factors, thickness, width, initial angle and machine, that all the factors have influence on the springback of the sheet-metals, although from the regression coefficients, the springback is most sensitive to the thickness of the bend of the sheet-metals. As inferred through the graphical plot presented in Figs. 4 and 5, springback decreases with the increase in the sheet thickness. In contrast to this relation, the influence of the bend angle on the springback is high, but the relationship is negative. The third influencing parameter according to the regression coefficient is the width, which also shows the linear relationship between the width and the springback, and it has been observed that in most of the cases, springback reduces with the width of the strip. The least influential parameter on the springback is the machine configurations which are observed from the low coefficient of regression. It is also analyzed that the combined effect of these parameters on the springback is not noticeable. The *P*-values greater than 0.05 state that there is not prominent relationship between the springback

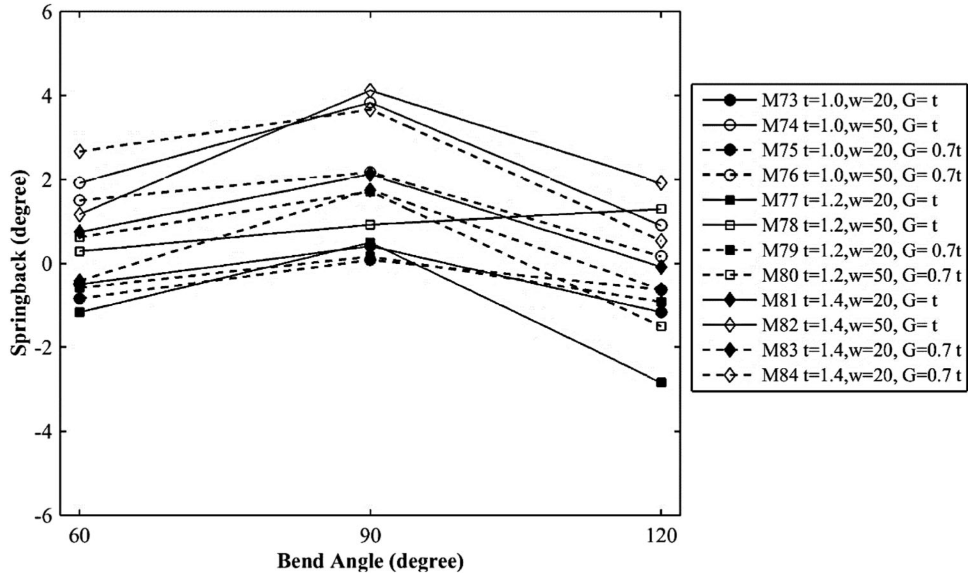


Fig. 16 Bend angle versus springback in JSC590 steel sheet-metals bent using the mechanical press

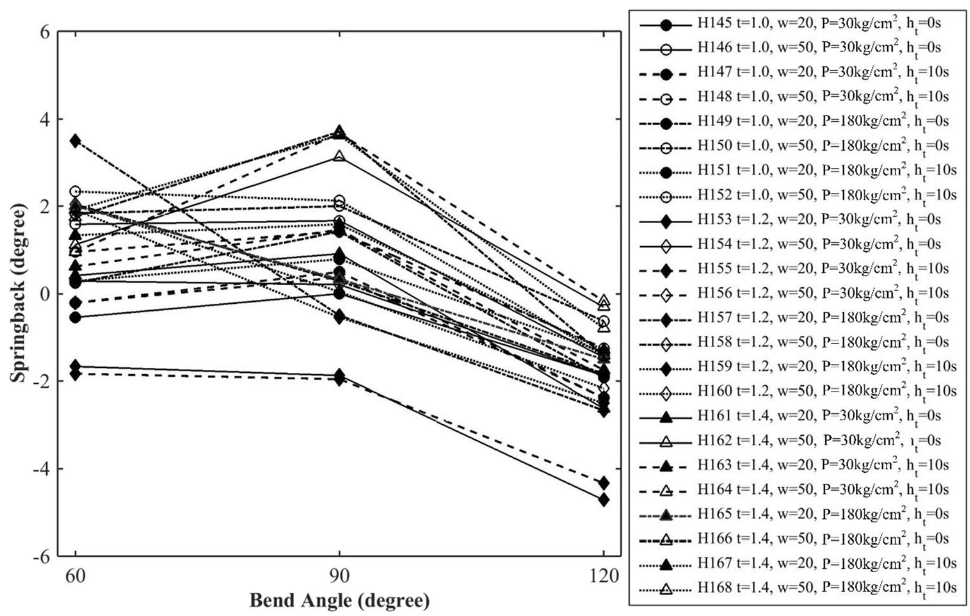


Fig. 17 Bend angle versus springback in JSC590 steel sheet-metals bent using the hydraulic press

and the factors, although interaction factor of width and machine has some influence on the springback of JSC590 steel sheet. Few insignificant relationships are observed with in the graphical plot discussed earlier.

5 Analytical Springback Model for JSC440 and JSC590

Regression models for the springback in JSC440 and JSC590 steels have been developed using the experimental data obtained. The following equation presents the regression model relating the significant factors influencing the springback in two types of materials. Equations 1 and 2 show the regression model for the springback in JSC440 and JSC590 steels, respectively.

$$\begin{aligned}\mathrm{SA} = {} & 12.27 - 29.9t - 0.0493w + 0.0434A + 14.06t^2 \\ & - 0.000820A^2 + 0.0390t \cdot w + 0.0379t \cdot A \\ & + 0.000372w \cdot A\end{aligned} \quad (1)$$

$$\begin{aligned}\mathrm{SA} = {} & 31.65 - 74.5t + 0.0486w + 0.2754A + 31.94t^2 \\ & - 0.001713A^2 - 0.0046t \cdot w - 0.0029t \cdot A \\ & + 0.000041w \cdot A\end{aligned} \quad (2)$$

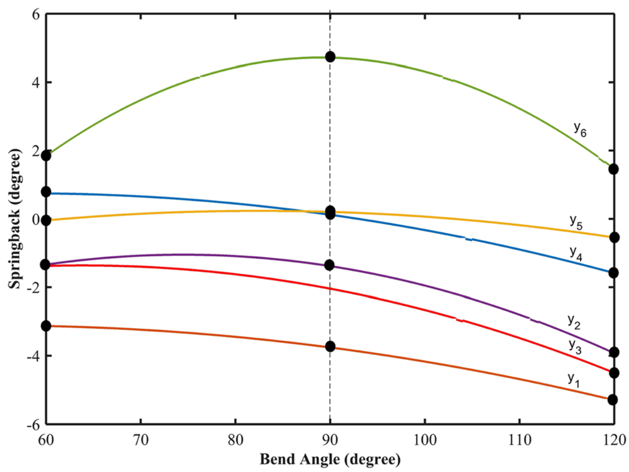


Fig. 18 Quadratic curves to predict the springback in the JSC440 steel sheet-metals

where SA, t, w and A are the springback, thickness, width and the bend angle, respectively.

Using the experimental data, analytical models for the springback for the different set of parameters for the JSC440 and JSC590 steels are developed (see Tables 11, 12). These models relate the springback to the bend angle, making the model simplified for the users. Using the MATLAB curve fitting workbench, quadratic curves are fitted on the data of bend angle against the springback. Maximum error of fitting curve is found to be 1.1 min of springback. Springback analytical models are also plotted and shown in Figs. 18 and 19. Figures show the springback variation in JSC440 and JSC590 steel sheet-metals, respectively, using the newly developed analytical model. Here, y-axis represents the springback and θ represents the bent angle. By putting any value to θ ranging between 60° and 120°, springback can be determined using these equations for the appropriate set of bending parameters. The experimentally determined springback at the angle 60°, 90° and 120° are also plotted on the curves as the dotted points. These analytical models can be used to predict the springback in JSC440 and JSC590 steel sheets by putting bend angle or interpolation between the curves.

6 Conclusion

In contrary to the formerly presented analytical model [1], different behavior of springback is observed in the high-tensile strength steel (JSC440 and JSC590). Negative springback also exists in these kind of materials. It can be inferred from the experimental analysis that

- No relationship exists for the springback in JSC590 steel and thickness of the blank, whereas, in case of JSC440 steel, springback increases for the higher thicknesses in most of the cases.
- The high-tensile strength sheet-metals also possess negative springback due to the high residual compressive stresses within the bend.
- In both JSC440 and JSC590 steels, springback is reduced as the width of the sheet-metal strips is increased; it is due to the distribution of residual stresses over the width of the blank.
- High magnitude of springback is observed at 90° bends, as compared to the 60° or 120° bends. It may be due to the acute angle of bends, where the tensile residual stresses override the compressive stress, causing the high positive springback.

Table 5 Analysis of variance for the springback in JSC440 steel sheets

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	17	430.083	25.299	26.76	0.000
Linear	5	394.262	78.852	83.41	0.000
Thickness (mm)	2	222.875	111.437	117.87	0.000
Width (mm)	1	23.225	23.225	24.57	0.000
Bend angle (degree)	2	148.162	74.081	78.36	0.000
Two-way interactions	8	34.312	4.289	4.54	0.000
Thickness (mm)*width (mm)	2	2.335	1.168	1.23	0.296
Thickness (mm)* bend angle (degree)	4	22.996	5.749	6.08	0.000
Width (mm)* bend angle (degree)	2	8.981	4.490	4.75	0.011
Three-way interactions	4	1.510	0.377	0.40	0.809
Thickness (mm) * width (mm) * bend angle (degree)	4	1.510	0.377	0.40	0.809
Error	90	85.086	0.945		
Total	107	515.170			

Table 6 Analysis of variance for the springback in JSC590 steel sheets

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	17	253.953	14.9384	15.53	0.000
Linear	5	236.884	47.3768	49.24	0.000
Thickness (mm)	2	47.339	23.6693	24.60	0.000
Width (mm)	1	53.142	53.1419	55.23	0.000
Bend angle (degree)	2	136.404	68.2019	70.88	0.000
Two-way interactions	8	12.776	1.5970	1.66	0.119
Thickness (mm)*width (mm)	2	0.409	0.2043	0.21	0.809
Thickness (mm)* bend angle (degree)	4	10.712	2.6781	2.78	0.031
Width (mm)* bend angle (degree)	2	1.655	0.8276	0.86	0.427
Three-way interactions	4	4.292	1.0730	1.12	0.354
Thickness (mm) * width (mm) * bend angle (degree)	4	4.292	1.0730	1.12	0.354
Error	90	86.598	0.9622		
Total	107	340.551			

Table 7 Process parameters for the minimum and maximum springback in the JSC440 steel strips bent using the mechanical press

Thickness (mm)	Minimum springback	Optimal parameters	Maximum springback	Parameters
1.0	− 1.333 (sample M3)	Width = 50 mm, bend angle = 60°, dead end = *t*	− 5.291 (sample M10)	Width = 20 mm, bend angle = 120°, dead end = 0.7*t*
1.2	0.125 (sample M7)	Width = 50 mm, bend angle = 90°, dead end = *t*	− 4.500 (sample M9)	Width = 20 mm, bend angle = 120°, dead end = *t*
1.4	− 0.0417 (sample M1)	Width = 20 mm, bend angle = 60°, dead end = *t*	4.710 (sample M7)	Width = 50 mm, bend angle = 90°, dead end = *t*

Table 8 Process parameters for the minimum and maximum springback in the JSC440 steel strips bent using the hydraulic press

Thickness (mm)	Minimum springback	Optimal parameters	Maximum springback	Parameters
1.0	0.208 (sample H4)	Width = 20 mm, bend angle = 60°, bend load = 180 ton, holding time = 10 s	4.792 (sample H18)	Width = 20 mm, bend angle = 120°, bend load = 30 ton, holding time = 10 s
1.2	0.583 (sample H6)	Width = 50 mm, bend angle = 60°, bend load = 30 ton, holding time = 10 s	3.875 (sample H18)	Width = 20 mm, bend angle = 120°, bend load = 30 ton, holding time = 10 s
1.4	0.375 (sample H21)	Width = 50 mm, bend angle = 120°, bend load = 30 ton, holding time = 0 s	3.792 (sample H15)	Width = 50 mm, bend angle = 90°, bend load = 180 ton, holding time = 0 s

- From the results of the ANOVA, it is observed in the JSC440 steel that the bend angle and the thickness of the sheet-metals have high influence on the springback in JSC440 steel sheet-metals, whereas the effect of width is smaller.
- There is a negligible effect of machine tool, gap between the die and punch at the dead center and the holding time observed during the V-bending in the JSC440 steel sheet-metals.
- In the JSC590 steel sheet-metals, it has been observed that no direct effect of parameters exist on the springback, whereas the springback minutely decreases with the increase in the width of the sheet-metals bent using the hydraulic press.

Table 9 Process parameters for the minimum and maximum springback in the JSC590 steel strips bent using the mechanical press

Thickness (mm)	Minimum springback	Optimal parameters	Maximum springback	Parameters
1.0	0.083 (sample M18)	Width = 20 mm, bend angle = 90°, dead end = 0.7t	3.833 (sample M19)	Width = 50 mm, bend angle = 90°, dead end = t
1.2	0.167 (sample M18)	Width = 20 mm, bend angle = 90°, dead end = 0.7t	− 2.833 (sample M21)	Width = 20 mm, bend angle = 120°, dead end = t
1.4	0.083 (sample M21)	Width = 20 mm, bend angle = 120°, dead end = t	4.128 (sample M19)	Width = 50 mm, bend angle = 90°, dead end = 0.7t

Table 10 Process parameters for the minimum and maximum springback in the JSC590 steel strips bent using the hydraulic press

Thickness (mm)	Minimum springback	Description	Maximum springback	Description
1.0	0 (sample H33)	Width = 20 mm, bend angle = 90°, bend load = 30 ton, holding time = 0 s	− 2.375 (sample H42)	Width = 20 mm, bend angle = 120°, bend load = 30 ton, holding time = 10 s
1.2	0.041 (sample H39)	Width = 50 mm, bend angle = 90°, bend load = 180 ton, holding time = 10 s	− 4.708 (sample H41)	Width = 20 mm, bend angle = 120°, bend load = 30 ton, holding time = 0 s
1.4	− 0.166 (sample H46)	Width = 50 mm, bend angle = 120°, bend load = 30 ton, holding time = 10 s	3.708 (sample H39)	Width = 50 mm, bend angle = 90°, bend load = 180 ton, holding time = 0 s

Table 11 Equations of the quadratic curves to predict the springback in the JSC440 steel sheet-metals

Curve	Parameters	Equation
y_1	t = 1.0 mm, w = 20 mm,	$y = -0.0005093\theta^2 + 0.05556\theta - 4.625$
y_2	t = 1.0 mm, w = 50 mm,	$y = -0.001389\theta^2 + 0.2069\theta - 8.75$
y_3	t = 1.2 mm, w = 20 mm,	$y = -0.001\theta^2 + 0.1271\theta - 5.417$
y_4	t = 1.2 mm, w = 50 mm,	$y = -0.0006\theta^2 + 0.06944\theta - 1.25$
y_5	t = 1.4 mm, w = 20 mm,	$y = -0.00056\theta^2 + 0.09167\theta - 3.542$
y_6	t = 1.4 mm, w = 50 mm,	$y = -0.0034\theta^2 + 0.6063\theta - 22.29$

Table 12 Equations of the quadratic curves to predict the springback in the JSC590 steel sheet-metals

Curve	Parameters	Equation
y_7	t = 1.0 mm, w = 20 mm,	$y = -0.00139\theta^2 + 0.2389\theta - 9.833$
y_8	t = 1.0 mm, w = 50 mm,	$y = -0.00269\theta^2 + 0.4667\theta - 16.42$
y_9	t = 1.2 mm, w = 20 mm,	$y = -0.00278\theta^2 + 0.4722\theta - 19.5$
y_{10}	t = 1.2 mm, w = 50 mm,	$y = -0.00015\theta^2 + 0.04333\theta - 1.775$
y_{11}	t = 1.4 mm, w = 20 mm,	$y = -0.00199\theta^2 + 0.3444\theta - 12.75$
y_{12}	t = 1.4 mm, w = 50 mm,	$y = -0.00287\theta^2 + 0.5292\theta - 20.25$

Each curve in these tables is named as y_1, y_2, etc. for the designated thickness and width of the blank

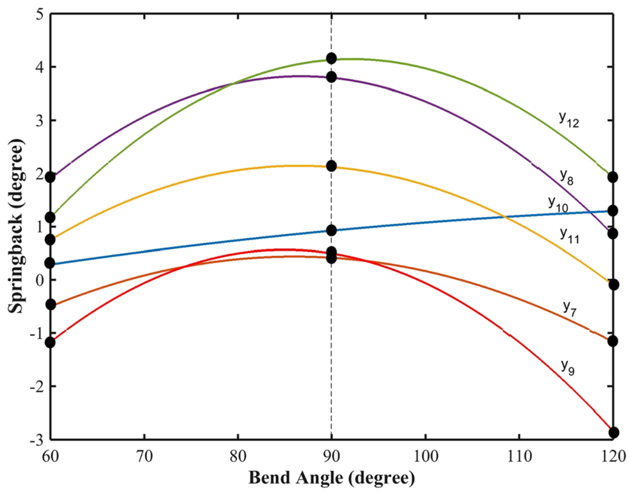


Fig. 19 Quadratic curves to predict the springback in the JSC590 steel sheet-metals

- It can be stated that an interaction effect exists on the springback of the JSC590 steel of the simultaneous change in width and using the hydraulic press.
- Exceeding the tonnage of the load does not minimize the springback, whereas reducing the gap between the punch and die at the dead end also does not affect springback.
- Optimal values for significant factors influencing the springback in JSC440 and JSC590 steels have been determined and presented in the article for the least springback.

Analytical models for the prediction of the springback have been developed, which can be used to predict the springback in the JSC400 and JSC590 steels sheet-metals of different thicknesses, widths, bend angle (from 60° to 120°) and the machine tool parameters. These analytical models can predict either negative or positive springback in the high-tensile strength sheet-metals. Based on the experimental investigation of the high-tensile strength sheet-metals, it can be stated that the negative springback in these sheet-metals is more dominant rather than the positive springback which exists in the low-tensile-strength sheet-metals. Hence, negative springback can be further studied by varying the parameters which are kept constant in this research.

Acknowledgements We are thankful to Mr. Fahad Qamar, Mr. Sadequain, Mr. Ozair Mustafa, Mr. Sohaib Ahmed Khan and Mr. Arsalan Zaidi for providing assistance in experimentation and arrangements in the tool design laboratory.

Funding This research project is funded by the NED University of Engineering and Technology, Karachi.

References

1. Kalpakjian S, Schmid S, *Manufacturing Engineering and Technology (7th)*, Pearson Higher Ed., London (2013).
2. Lang K, *Hand Book of Metal Forming (2nd)*, Society of Manufacturing Engineering, Dearborn (1994).
3. Cardena W D, Genga L M, Matlockb D K, and Wagoner R H, *Int J Mech Sci* **44** (2002) 79.
4. Tekinar Z, *J Mater Process Tech* **145** (2004) 109.
5. Fei D, and Hodgson P, *Nucl Eng Des* **236** (2006) 1847.
6. Dong-juan Z, Zhen-shan C, Zhi-ying C, and Xue-yu R, *J Zhejiang Univ-SC A* **8** (2007) 237.
7. Ozturk F, Toros S, and Kilic S, *J Iron Steel Res Int* **16** (2009) 41.
8. Inamdar M V, Date P P, and Sabnis S V, *J Mater Process Tech* **123** (2002) 459.
9. Ramezani M, Ripin Z M, and Ahmad R, *Int J Adv Manuf Tech* **46** (2010) 101.
10. Swiotoniowski A, and Balon P, *J KONES Powertrain Transp* **19** (2012) 459.
11. Slota J, and Jurcisin M, *Mechanika* **284** (2012) 55.
12. Da Silva E A, Fernandes L F, Silva J W, Ribeiro R B, Pereira M D, and Alexis J, *IOSR J Mech Civ Eng* **13** (2016) 21.
13. Yang X, Choi C, Sever N K, and Altan T, *Int J Mech Sci* **10** (2016) 266.
14. Jung J, Jun S, Lee H S, Kim B M, Lee M G, and Kim J H, *Metals* **7** (2017) 1.
15. Choi J, Lee J, Bong H J, Lee M G, and Barlat F, *Int J Solids Struct* **151** (2018) 152.
16. Leu D K, and Zhuang Z W, *J Mech Sci Technol* **30** (2016) 1077.
17. Cai Z H, Batthyány P, Dhawan S, Zhang Q L, Sun Y H, Luan X, Wang L L, and Gharbi M M, *Adv High Strength Steel Press Hardening* **1** (2019) 117.
18. Nakagawa Y, Mori K, and Maeno T, *Int J Adv Manuf Tech* **95** (2018) 456.
19. Noma N, Hashimoto K, Maeda T, and Kuwabara T, *J Phys Conf Ser* **1063** (2018) 1.
20. Liu C G, Yue T, and Yu X T, *Int J Precis Eng Man* **20** (2019) 217.
21. Liu C, Yan X D, Yang Y, and Ye W, *Mater Sci Forum* **944** (2019) 753.
22. Ramadass R, Sambasivam S, and Thangavelu K, *J Braz Soc Mech Sci* **41** (2018) 21.
23. Lin J, Hou Y, Min J, Tang H, Carsley J E, and Stoughton T B, *Int J Mater Form* (2019). https://doi.org/10.1007/s12289-018-0146.
24. Minitab, Minitab LLC. USA (2019). www.minitab.com.
25. MATLAB, Mathworks Inc. USA (2019). https://www.mathworks.com/products/matlab.html.