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Analysis and optimization of springback during the V-bending of hot-rolled high-strength steels (JSH440)

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ABSTRACT

Influences of thickness, width, bend angle, applied load, and holding time are evaluated over the springback in hot-rolled, high-tensile strength sheet-metals (JSH-440). Blanks' thickness, width, and bend angles are considered the geometric parameters, whereas applied load and holding time are the process parameters considered in the research. Analysis of variance (ANOVA) and sensitivity analysis are applied to evaluate the significance of the factors over the springback magnitude. Analytical models are developed to predict the springback in the sheet metals for the desired geometric and process parameters. Simplified analytical models are also developed for different geometries of sheet metals. Finally, the Genetic Algorithm has also been applied to determine the optimal process parameters for the minimum springback with varying geometries of the sheet metals. Finally, the influences of parameters and optimized results are discussed in detail.

Keyword: High-tensile strength; Sheet metals; V-bending; Springback; JSH440.

INTRODUCTION

Cold or hot-rolled metal sheets with a very high length to thickness ratio are called sheet metals (Kalpakjian, 2014). Sheet metal components are formed by bending, drawing, or forming processes to generate different mechanical components, such as automotive, household, aircraft, and electronic equipment. The use of high-tensile strength sheet metals has grown in the automobile and aircraft industry, usually in reinforcement parts due to higher specific strength and good impact resistance for safety and fuel efficiency. Specific manufacturing processes are used to produce sheet metal parts, such as bending, forming, drawing, piercing, blanking, perforating, lancing, spinning, and so on.

To form the desired geometry of the final product, bending of sheet metal is the most widely used process in the industry (Kalpakjian, 2014). It is the permanent deformation of sheets, forming bends in sheet metals. Four primary sheet metal bending processes are V-bending, rotary bending, edge bending, and air bending (shown in

Fig. 1). In the V-bending process, a set of die (female part) and punch (male part) is used to draw the sheet metal and provide bend as that in the cavity (see Fig. 1(a)).

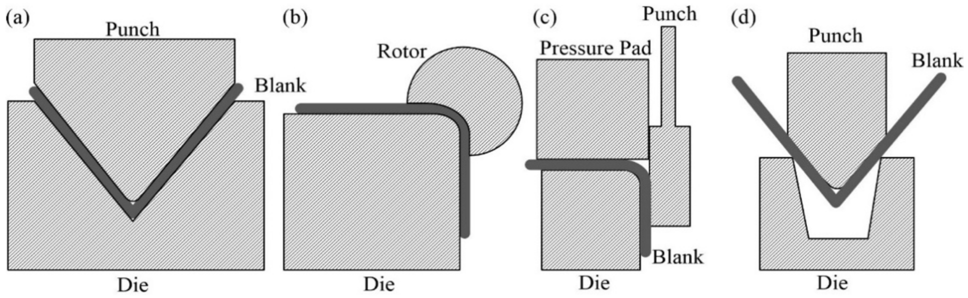

Figure 1. Bending processes for the sheet metals. (a) V-bending, (b) Rotary bending, (c) Edge bending, and (d) Air bending.

The V-bending process can produce acute, right, and obtuse angles using a die set operated in a machine tool. Pressure is gradually applied to the punch using a mechanical, hydraulic, or pneumatic press transmitted to the blank. The blank plastically bends within the cavity formed within the die set. When the pressure is removed and the punch is moved away from the blank, the blank tries to recover its shape. This elastic recovery in sheet metals due to the residual stresses is called springback and is illustrated in Fig. 2 (Lang, 1994). This elastic recovery can either be outside or inside the bend. Hence, it is recognized by negative or positive springback, which entirely depends on the sheet metal's properties and geometries (Lang, 1994).

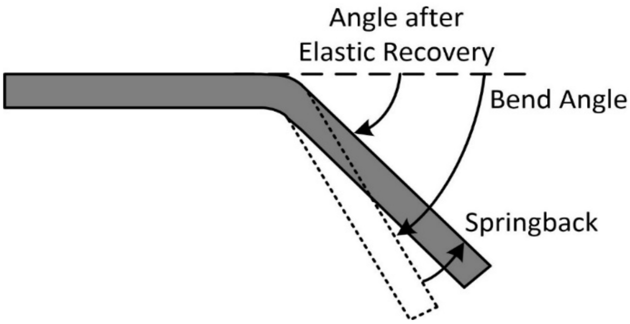

Figure 2. Illustration of springback during the bending of sheet metal.

Many parameters impact the springback in sheet metals. A few of these factors are mechanical properties, thickness, bend width, bend radius, bend angle, type of machine tool, the power source of machine tools, and tooling geometry (Kalpakjian, 2014) (Lang, 1994).

Negative springback is widely observed in high-tensile strength sheet metals, especially in Steel. In this research, this nature of springback is specially investigated with the positive springback, seldom addressed in analytical models (Kalpakjian, 2014) (Lang, 1994). Thorough literature has been reviewed to investigate the behaviour of springback in hot-rolled high-tensile strength sheet metal.

Cardena et al. (2002) reported relationships of springback with the mechanical properties of ordinary Steel and Aluminium sheet metals. Inamdar et al. (2002) developed an experimental setup for the air bending of sheet metal with varying mechanical properties. Using various geometries of die set and blank geometry, they studied the pattern of springback. Tekinar (2004) selected the air bending process and experimentally determined the impact of blank and modular die set geometry over the springback in Steel (nongalvanized and galvanized), Brass, Copper, and Aluminium sheet metals. Fei and Hodgson (2006) investigated the behaviour of springback in TIRP steel for the various types of sheet metal and their mechanical properties. The coefficient of friction is found to be one of the critical factors affecting the springback. Dong-juan et al. (2007) developed a mathematical model of springback depending upon Hill's yielding criterion along with the plane strain condition. Ozturk et al. (2009) used a sheet metal rolling setup for the DP steels and presented the behaviour of springback by varying rolling directions and applied temperature. Ramezani et al. (2010) used the FEM approach and related the kinetic friction with the springback during the V-bending process of ultrahigh-tensile steels. Slota and Jurcisin present another springback prediction model for the TRIP, AHSS, and mild Steel during the air-bending process (Slota and Jurcisin, 2012). A comparative analysis for the springback is presented in Da Silva et al. This research differentiates the behaviour in springback in advanced high-tensile strength material sheet-metals (DP600 and DP780) during the air-bending process (Da Silva et al., 2016). Leu and Zhuang (2016) used the finite element modelling technique to develop a springback model in high-strength sheet metals (cold-rolled SPFC 440 and SPFC 590) to optimize the blank thickness, mechanical properties of the material, and die-set geometry. Yang et al. (2016) performed experimental analysis on springback in advanced high-strength steel (DP780) by varying process parameters during the air-bending process. They also used the experimental data to develop an analytical model to predict springback in these metals. Jung et al. (2017) presented a springback prediction model for the U-bending of dual phased-steels using the experimental data. Ramadass et al. (2018) minimized the springback in Titanium grade steel sheets, using the finite element modelling and experimental technique by optimizing blank, die set geometry, and the process parameters. Choi et al. (2018) used FEM modelling and experimental validation of springback for the single and double stage U-bending in TWIP 980 sheet metals.

Nakagawa et al. (2018) analysed the effect of quenching, after the sheet metal stamping process, over the springback in ultra-high-strength Steel thin sheets with a tensile strength of 1.5 GPa. Noma et al. (2018) developed a unique strength differential model (SDM) based on the FEM technique for the springback in very high-tensile strength sheet metals (tensile strength more than 980 MPa). This model can predict the springback in sheet metals for different mechanical properties and blank geometries. Liu et al. (2019a, 2019b) developed FEM models and analysed the springback in different geometries of reinforcement members. They studied the effect of springback during the milling process over the titanium square tubes. Experimental results show that springback is directly proportional to the radius of bent tubes. Cai et al. (2019) studied the behaviour of springback by increasing temperature during the U-bending process over the high-strength aluminium alloy (AA6082). Lin et al. (2019) developed a springback FEM model for the bending of U-Channels of MP980 and AA6022-T4. They concluded that the yield criteria are an essential parameter for improved accuracy of springback prediction in FEM models. Ren et al. (2019) presented an in-progress springback compensation technique for the sheet metal part with arbitrary geometry having a tensile strength of 68 GPa. Balon et al. (2019) performed FEM analysis for the springback during the cold and hot forming on the specific geometry of blanks of HCT 780X steel. They concluded that higher springback is observed during the cold forming of sheet metals. Pornputsiri and Kanlayasiri (2019) performed an analysis of springback concerning change in the microstructure of Transformation Induced Plastic Sheets (TRIP) by adopting real-time heat controlling techniques. In another research, Leu et al. (2019) presented a mathematical model relating mechanical properties of SPFC 440 (cold-rolled) with the limited geometric parameters of the sheet metal blank and elastic recovery during the V-bending process. Wasif et al. (2020) presented research consisting of springback analysis during the V-bending in high-strength steels (JSC440 and JSC590) along with the analytical model and optimization results. Cui et al. (2020) presented a unique experimental analysis, where magnetic flux has been applied during the bending, which provided promising results. Umur et al. (2020) performed an experimental investigation of springback in DP600 and DP780 sheet metals by varying thickness, die curvature, and punch tip radius.

The literature cited above shows the effects of springback on several types of sheet metals. Several models are reported in the earlier research relating the geometry of blank, die set, and process parameters with the springback. These models are specific to the materials and depend on the composition of sheet metals. It is observed from the extensive literature review that in each of the research, two to three process parameters have been analysed for the specific types of sheet metals. In continuation with the previous research, an extended analysis of springback due to bend angle, thickness and width of the sheet, applied press load, and holding is performed over the hot-rolled high-tensile strength steels (JSH440). V-bending of different angles has been applied over the blanks of JSH440 with varying widths and thicknesses. Machine tools parameters, applied load, and holding time are also considered to study their influence over the springback. An analytical model for the springback is also presented, which relates blank geometry and machine tool parameters to the springback. Optimization of these parameters is performed to minimize the springback. At the same time, the influence of these parameters over the springback is discussed in detail. The research clearly shows that the negative springback exists in hot-rolled high-tensile strength steel, which cannot be predicted with the generic analytical models. These depend on the materials' mechanical properties and do not incorporate the compressive behaviour during the springback (Wasif et al., 2020). Furthermore, the analytical models of springback presented in this research can predict the springback in JSH440 with the five process parameters.

METHODOLOGY

Hot-rolled high-tensile strength steel is widely used in the automobile and machine tool industry due to its extensive properties and availability. The industry's' main requirement is to predict the springback in high-tensile strength material for the different settings of process, tool, and blank geometry parameters and optimize those for the minimum springback. Hence, in this research, experimental investigation has been performed to analyse springback behaviour in hot-rolled high-strength sheet metals (JSH440), to facilitate the industry with optimized outcomes of springback. According to the material composition of JSH440, it contains the following elements by weight for maximum of 2% Manganese (Mn), 0.1% Columbium (Nb), 0.25% Carbon (C), 0.1% Titanium (Ti), 0.03% Sulphur (S), 0.6% Silicon (Si) , 0.05% Phosphorus (P), 0.1% Boron (B), 0.1% Aluminium (Al), and rest of 96.67% of Ferrous (Fe) (JFE Steel Corp, 2019).

Experiments are designed to analyse the impact of blank geometry and bending parameters over the springback in JSH440 steel. A hydraulic press of load up to 75 tons has been selected to perform the v-bending of JSH440 sheet metal. Three sets of bending punch and die, made of medium carbon steel, have been developed to bend sheet metal strip to angles of 60°, 90°, and 120°. A digital bevel gauge is used to measure the bend angles of metal strips. Design of experiment (DOE) has been employed to setup up different combinations of process parameters for the V-bending of JSH440. Process parameters related to the blank geometries are bend angle, the width of strip, and thickness of the strip, whereas process parameters related to machine tools are applied load and blank holding time between the die and the punch. Each experiment is repeated thrice in random manner to eliminate the biasness in the data gathering. Measurements of bend angles through the digital bevel gauge have been collected through the experimental results, investigating the effects of varying process parameters over the springback. Analysis of Variance (ANOVA) is applied over the experimental results to determine the most influential parameters affecting the springback in JSH440. Results of springback are plotted against each process parameter to investigate the trend of outcome with respect to the varying process parameters. Mathematical models have been established using the experimental data to predict springback during the V-bending of JSH440 sheet metals, with different combinations of the parameters. Finally, optimal bending parameters for different geometry of blanks are presented with minimum springback in JSH440 during the V-bending process.

EXPERIMENTAL SETUP

The experiments' factorial design is applied to analyse the effects of blank geometry and machine tool parameters over the springback during the V-bending of hot-rolled high-tensile strength steel (JSH440). Five essential controllable parameters, including blank geometry and machine tools parameters, have been selected to study the springback behaviour to limit the number of experiments in the research. A 75-ton hydraulic press with varying applied load of 30 $kgcm^{-2}$ and 180 $kgcm^{-2}$ is selected. Table 1 presents the process parameter along with the varying levels. Table 2 illustrates the controllable parameters kept unvaried.

Each bend is replicated to avoid human error, and the average value of two bend angles is taken as the final springback. The sequence of bending is selected randomly to avoid the biases of results. It is also to be noted that the source of the sheet metal strips is single and standardized. Hence, there is no need for blocking during the design of experiments. Sheet metal blanks are bent up to the defined angles using the hydraulic press, which angles are measured using a digital bevel protector. Forty-eight experiments with varying parameters 6 are designed, which are replicated once. Hence, a total of 96 strips are bent. Measured springback data is gathered and statistically analysed using the Minitab Educational Version (Minitab, 2019).

Table 1. Blank Geometry and Machine Tool Parameters.

S. No.	Parameter	Type	Levels		
			I	II	III
1.	Thickness – T (mm)	Blank Geometry	T1=1.4	T2=1.6	--
2.	Width – W (mm)		W1=20	W2=50	--
3.	Bend Angle - A (degree)		A1=60	A2=90	A3=120
4.	Load – L ($kgcm^{-2}$)	Machine Tool Parameter	L1=30	L2=180	--
5.	Holding Time – H (sec)		H1=0	H2=10	--

Table 2. Parameters kept constant.

Parameters	Value
Length of blank	170mm
Inner bend radius or radius of the punch	8mm
Outer bend radius or radius of the die	10mm

The main hypothesis of the research assumes that the controllable factors identified in Table 1 and their interactions do not influence the springback, and hence the mean springback achieved by varying the parameter levels remains the same. Alternate hypothesis assumes vice versa. That is, varying levels of the parameters or their interactions affect the mean springback. Hence, Analysis of Variance (ANOVA) will be applied to the data of springback to assess the trueness of the hypothesis.

ANALYSIS OF SPRINGBACK

ANOVA depicts the significance of the influence of controllable parameters over the response variable. Table 3 shows the ANOVA applied to the springback data gathered through the measurement. In Table 3, the P-value for the specific F-value less than 5% depicts that the probability of occurrence of the main hypothesis for the controllable factors or their interactions does not lie within 95% confidence interval. Hence, alternate hypothesis is true, and the factors or their interactions do not significantly influence the springback. In the case of P-value being higher than 5% depicts that the main hypothesis is true, and the factors or their interaction do not significantly influence the springback.

ANOVA presented in Table 3 suggests that the blank geometry parameters, thickness, width, and bend angle are the significant factors that influence the springback since their P-values are less than 5% (0.05). At the same time, load and holding time do not significantly influence the springback having P-values higher than 0.05. It can also be seen from the same table that the interactions of the factors also insignificantly influence the springback. From Table 3, the highest influencing factor over the springback is thickness having the highest F-value of 62.44. Bend angle and thickness are the other factors influencing springback with F-values of 55.9 and 15.31, respectively. To further investigate the behaviour of springback, springback data gathered through the measurements are plotted against each of the process parameters (shown from Fig. 3 to Fig. 7). Each curve presented below shows the variation in springback due to the change in a single process parameter, keeping the other parameters constant. Variation in Springback during the V-bending of JSH440 due to different sheet thicknesses is shown in Fig.3. Here, each curve represents a sample bent using a specific set of process parameters. The black solid curve with a black circle marker is marked as S1 (see legends in Fig. 3). This curve represents the variation in springback due to the change of thickness from 1.4mm to 1.6mm while keeping constant parameters, which are press load to level 1 (L1), holding time to level 1 (H1), bend angle to level 1 (A1), and width of the strip to level 1 (W1).

Table 3. ANOVA for the Springback in JSH440 Sheet Metals.

Source	DOF	Adj. SS	Adj. MS	F-Value	P-Value
Thickness (mm)	1	60.767	60.7669	62.44	0.000
Width (mm)	1	14.899	14.8992	15.31	0.000
Bend Angle (Degree)	1	54.403	54.4032	55.90	0.000
Load	1	2.086	2.0865	2.14	0.153
Holding Time	1	0.211	0.2112	0.22	0.645
Bend Angle (Degree)*Bend Angle (Degree)	1	3.757	3.7567	3.86	0.058
Thickness (mm)*Width (mm)	1	0.178	0.1781	0.18	0.672
Thickness (mm)*Bend Angle (Degree)	1	0.325	0.3248	0.33	0.568
Thickness (mm)*Load	1	0.455	0.4552	0.47	0.499
Thickness (mm)*Holding Time	1	0.036	0.0361	0.04	0.849
Width (mm)*Bend Angle (Degree)	1	0.870	0.8698	0.89	0.352
Width (mm)*Load	1	1.473	1.4732	1.51	0.228
Width (mm)*Holding Time	1	0.222	0.2224	0.23	0.636

Bend Angle (Degree)*Load	1	1.166	1.1663	1.20	0.282
Bend Angle (Degree)*Holding Time	1	1.226	1.2261	1.26	0.270
Load*Holding Time	1	0.069	0.0687	0.07	0.792
Error	31	30.171	0.9732		
Total	47	172.315			

Fig. 3 shows the variation in springback due to a change in JSH440 sheet thickness. Fig 3(a) shows that both positive springback and negative springback exist in JSH440 sheet metal strips, which vary with the change in thicknesses. Upward trends in curves above the zero springback show the increase in the magnitude of springback, where the upward trend in the curve below the zero springback value mentions the decreasing magnitude of springback (refer to Fig. 3(a)). The highest magnitude of springback, 3.75 degrees, is observed in the strips having thickness of 1.4mm and bent with parameters levels L1, H1, A2, W2 (S4) and L2, H1, A2, W2 (S16). Here, it is common in both blanks that the holding time is zero, whereas, bent angle and width of the strips are 90° and 50mm, respectively. Springback in these strips is drastically reduced and reached up to a negative springback of -1 degree. The least springback is observed in curve S7, having the most negligible load, angle, and width but having a holding time of 10 seconds. From Fig. 3, negative springback is highly occurred in the blanks having obtuse bent angle (A3=120°) in curves S5, S6, S11, S17, S18, S23, and S24. The compressive residual stresses in the obtusely bent blanks dominated over the tensile one and caused the negative springback in the strips. Compared to moderate and low tensile strength materials, this phenomenon is only observed in high-tensile material, which is also evident in earlier research where cold-rolled high-tensile strength materials were used (Wasif et al., 2020). Despite the random occurrence of negative springback, it has been observed only in the blanks bent to 120°.

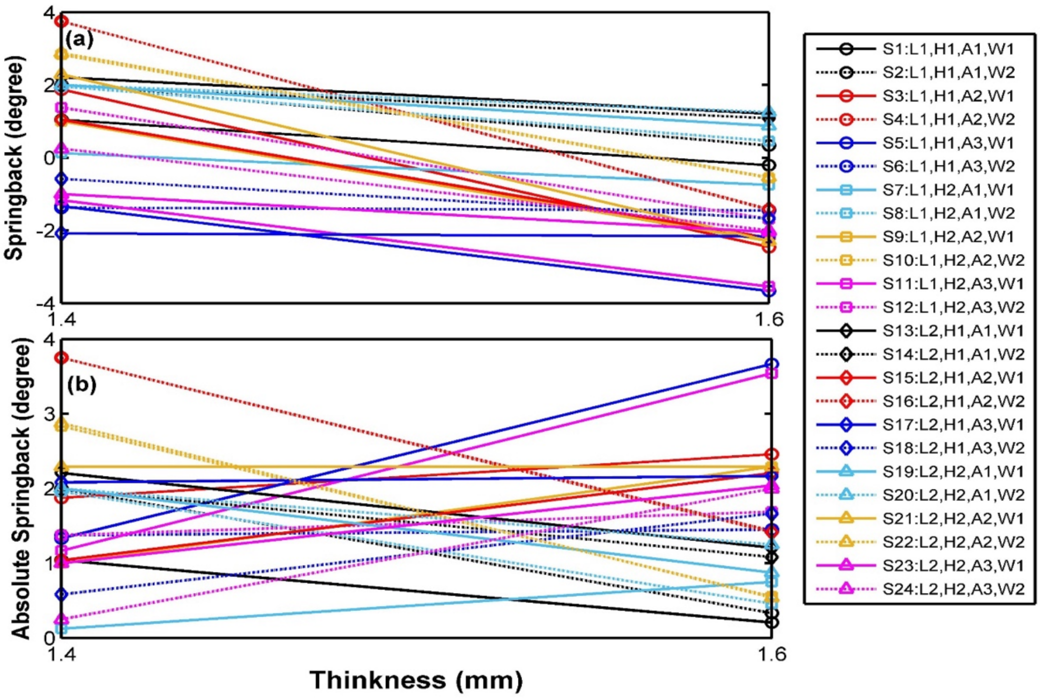

Figure 3. Variation in springback due to change in sheet metal thickness: (a) thickness versus springback, (b) thickness versus absolute springback.

Fig. 3(b) is drawn to present the absolute springback in the strips. Springback increases with the thickness, especially in the strips bent to 120°. High springback magnitudes are observed in the blanks bent to 120°, with the load of 30kgcm^{-2}, having a width of 20mm (curves S5 and S11). A slight increase in springback occurred when the strips are bent with the higher load of 180kgcm^{-2}. It is due to the applied load, which overcomes the residual stresses stored in the strips and prevents elastically deform. Form Fig. 3(b), in most dotted curves (having a width of 50mm), springback magnitude reduces with the thickness. An exception to this behaviour only exists in the strips bent to the angle of 120° (curves S18 and S24). Springback magnitude usually increases as the thickness is increased, in most of the strips having a thickness of 20mm (all solid colour curve). An exception has been observed in the curves S1, S13, and S19, where strips are bent to an angle of 60°. It may be due to the geometry of the strip bent to an acute angle, where compressive and tensile residual stresses within the bent are pretty low and balanced.

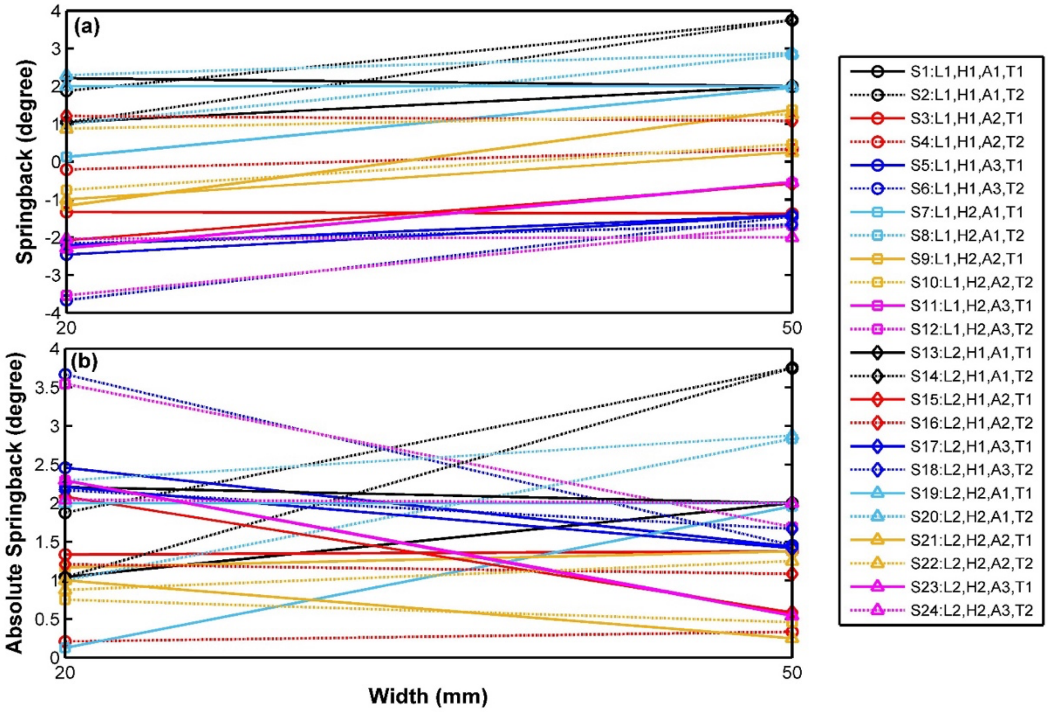

Figure 4. Variation in springback due to change in sheet metal width: (a) width versus springback, (b) width versus absolute springback.

Fig. 4 presents the influence of JSH440 strip widths over the springback. Fig. 4(a) shows that the strips bent to the angle of 60° possess positive springback, which generally increases with the width. The springback increase with the width, if it is bent to an acute angle, it is due to the large area around the bend of the strip storing more considerable tensile residual stresses, causing the positive springback. Negligible springback with the increase of width is observed in curves S3, S16, and S22. This springback is observed in the blanks bent to 90°, even with the load of 180 kg cm^{-2}. Contrary to this situation, negative springback occurred in most of the strips that bent to 90° and 120° as shown in Fig. 4(a) in curves S4-S6, S9-S12, S15-S18, and S21-S24. Fig 4(b) shows that negative springback in the strips reduces with the width bent to either 90° or 120°. Maximum springback occurred in the strips bent to an angle of 120°, having the width of 20mm with the thickness of 1.6mm (see curves S6 and S12) and in the strips bent to 60°, having the width of 50mm with the thickness of 1.6mm (see curves S2 and S14).

Fig. 5(a) shows positive springback in most of the strips bent at 60°. On the contrary, curves S3 and S7 show negative springback having a thickness of 1.6mm. Fig. 5(a) also shows that the positive springback generally occurs in the sheet metal strips having a thickness of 1.4mm (all the blue and black curves) bent within the acute angles. Negative springback occurred in few of these strips while bent to 120° (see curves S1, S5, S9, and S13 in Fig. 5(a)). Negative springback is seen in the strips bent to 120° having a thickness of 1.4mm due to the higher tensile residual stresses in the lower thickness bent. Fig. 5(a) also shows that negative springback generally exists in the strips having thicknesses of 1.6mm bent to 90° and 120°. It usually occurred in the strips (except S8 and S16) due to the bending at right and obtuse angles, causing dominant tensile residual stresses within the bend resulting in negative springback. Fig. 5(a) shows that the highest positive springback is observed in the strips bent to 90° having the thickness of 1.4mm and width of 20mm, whereas the highest negative springback is observed in the strips bent to 90° having a thickness of 1.6mm with the same width. Hence, springback nature shifts from positive to negative as the bent angle is increased from acute to obtuse angles.

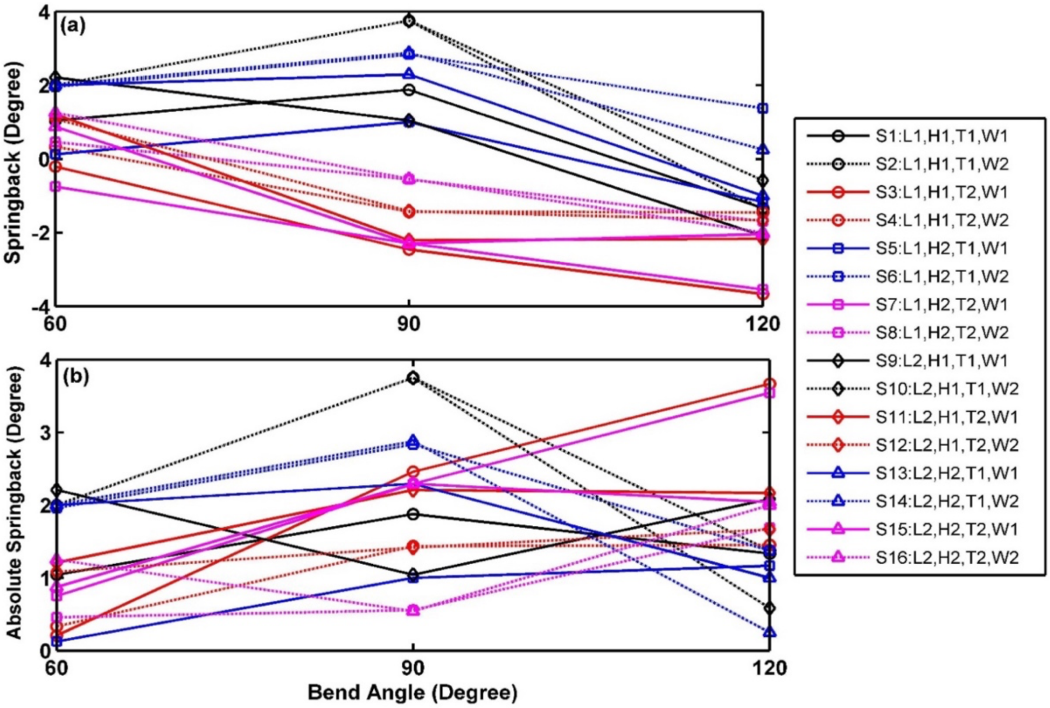

Figure 5. Variation in springback due to bent angles: (a) bent angle versus springback, (b) bent angle versus absolute springback.

From Fig. 5(b), the highest magnitude of springback is seen in the sheet metal blanks bent to 90°. It can be seen from the same figure that almost the same magnitude of springback occurs in the strips bent to 60° and 120°, where slightly higher magnitude is observed in the strips having a thickness of 1.6mm and width 20mm and bent to 120° (see Figures S3 and S7). In few cases, such as S3, S7, S11, and S15, the increase in bend angle causes the increase in springback magnitude (refer to Fig. 5(b)).

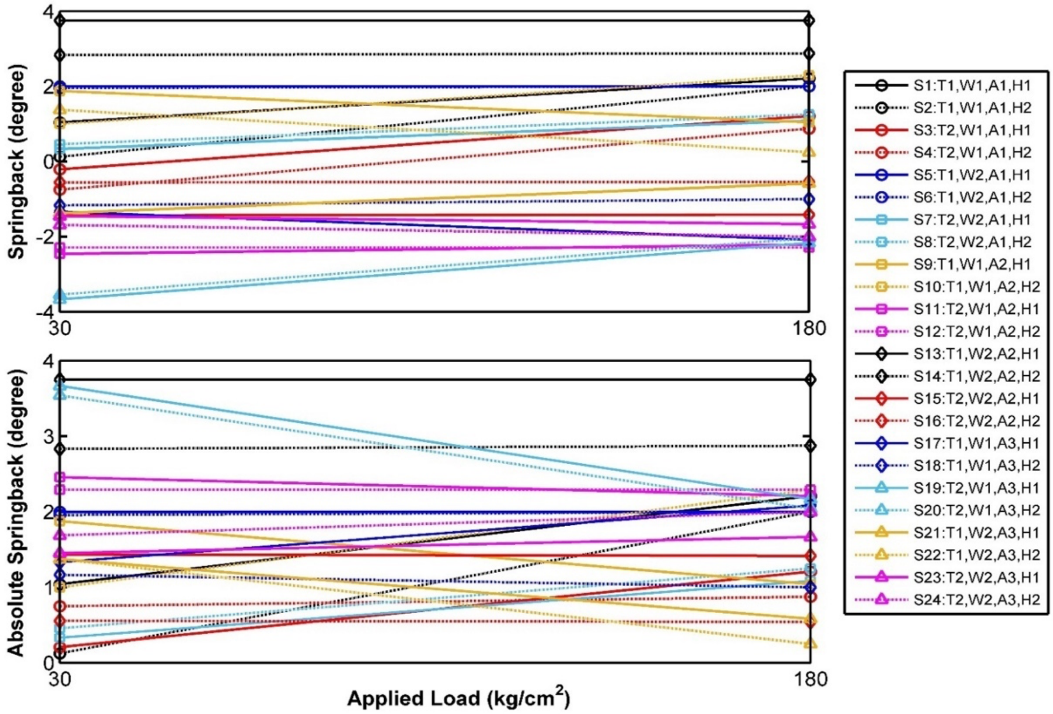

Figure 6. Variation in springback due to applied load: (a) applied load versus springback, (b) applied load versus absolute springback.

Fig. 6(a) shows the variation in springback behaviour with the change of applied load through the press. It shows that the highest positive springback is found over the strips bent to 90° (curves S13 and S14), having the width of 50mm, which remains the same with the different applied loads. The highest negative springback is observed in the strips bent to 120° with a minimum load of 30kgcm$^{-2,}$ having a thickness of 1.6mm (curves S19 and S20 in Fig. 6(a)). From Fig. 6(b), changing applied load has mixed response over different types of strips. Springback increases with the increase in applied load only in the strips having a bend angle of 60° and width of 20mm (as seen in curves S1 to S4).

In most cases, springback does not change with the change in applied load, as seen in the curves S5 to S16, whereas, springback decreases as the applied load increases only in the strips bend to 120°, with varying widths and thicknesses shown in the curves S16 to S24. Hence, applying increased load does not affect the residual stresses stored in the JSH440 sheets bent to acute angles, whereas applied load releases the residual stresses during v-bending of steel sheets if bent to obtuse angles minutely. Hence, based on ANOVA and Fig 6, it can be concluded that the varying load through the press does not significantly influence the springback.

In contrary to previous research, it can be seen from Fig. 7(a) that the effect of holding time on springback is relatively minor (Wasif et al., 2020). Negative springback in the strips bent to 120° never changes with the holding time, as seen in the curves S17 to S25 of Fig. 7(a). An exception has been observed in curve S21, where the springback changed its behaviour from negative springback to positive one without change in magnitude. Hence, no change has been observed magnitude-wise in this curve in Fig. 7(b). Reduction in springback occurred with the increase in holding time in curves S1, S2, S13, and S14 (see Fig. 7(b)). It can also be observed that few exceptions are seen in curves S3, S7, S10, and S24 that the springback magnitude increased with the increasing holding time in JSH440, which is a pretty exceptional case. It may be due to the high-tensile strength and that the residual stress got strong during the holding time. Hence, based on Table 3 and Fig. 7, it can be said that holding time does not significantly affect the springback.

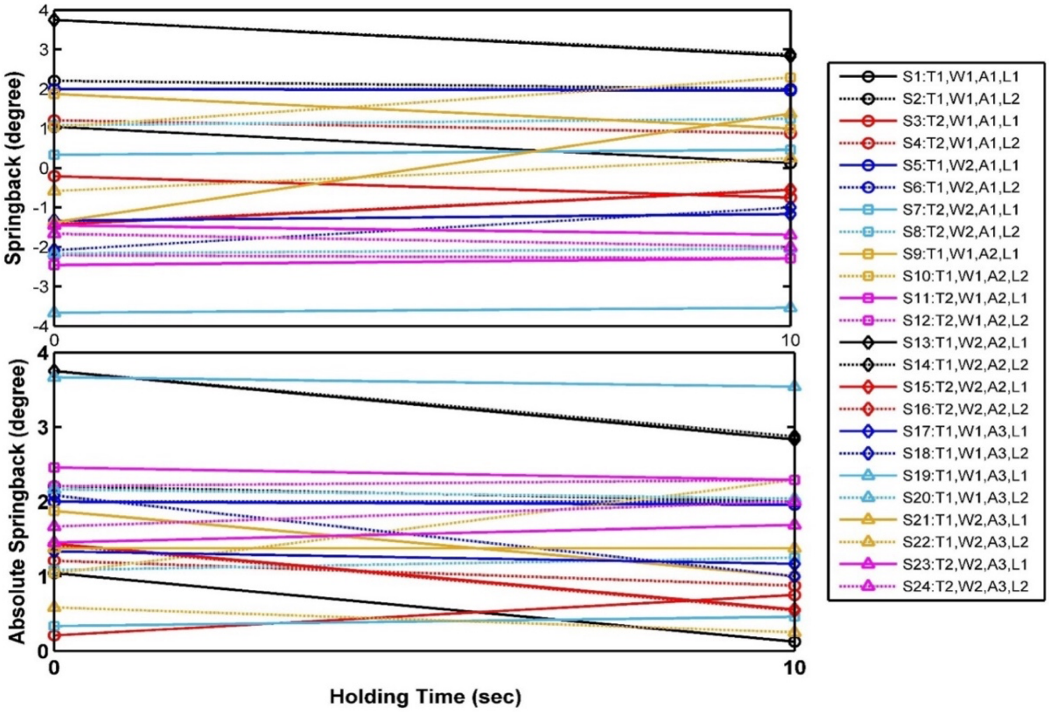

Figure 7. Variation in springback due to holding time: (a) holding time versus springback, (b) holding time versus absolute springback.

ANALYTICAL MODEL AND OPTIMIZATION

Analytical models of the springback in JSH440 sheet-metals are developed based on the measured springback in the metal strips. Eq. 1 presents the analytical model of springback for the JSH440 sheet metals, which relates the springback in the sheet metal with the controllable factors and their interactions. The model summary presents an R2 of 82.49%, a good percentage of fit to the model.

$$\begin{aligned} Springback &= 9.7 - 7.9T + 0.077W + 0.115A - 0.0041L - 0.064H - 0.0006A^2 - 0.0406T \cdot W \\ &\quad - 0.0336T \cdot A + 0.013T \cdot L - 0.055T \cdot H + 0.0004W \cdot A - 0.0001W \cdot L \\ &\quad + 0.0009W \cdot H - 0.0001A \cdot L + 0.0013A \cdot H + 0.0001L \cdot H \end{aligned} \quad (1)$$

Let T, W, A, L, and H be the sheet-metal thickness, width, bend angle, the load applied, and holding time of load. Each coefficient of the equation represents the weightage of the influence over the springback. The coefficients less than or equal to 10^{-5} are omitted to have insignificant influence over the magnitude of the springback.

Since it is entirely practised in the industry to determine springback in the sheet-metals analytically for the bend angles, simplified analytical models based on the bend angles are also developed for different thicknesses and widths of the blanks, which are presented in Table 4. Quadratic equations are fitted on the experimental data of springback related to the bend angle (see Fig. 8). Equations of the curves y_1, y_2, y_3, and y_4 for the prescribed thickness and width of the blank are presented in Table 4.

Table 4. Quadratic Equations for the prediction of springback in JSH440 Sheets Metals.

Blank Parameters	Curve	Equation	No.
t=1.4mm, w=20mm,	y_1	$= -0.0022A^2 + 0.3646A - 12.75$	(2)
t=1.4mm, w=50mm,	y_2	$= -0.0038A^2 + 0.6313A - 22.13$	(3)
t=1.6mm, w=20mm,	y_3	$= 0.0005A^2 - 0.1617A + 7.413$	(4)
t=1.6mm, w=50mm,	y_4	$= 0.0009A^2 - 0.2049A + 9.125$	(5)

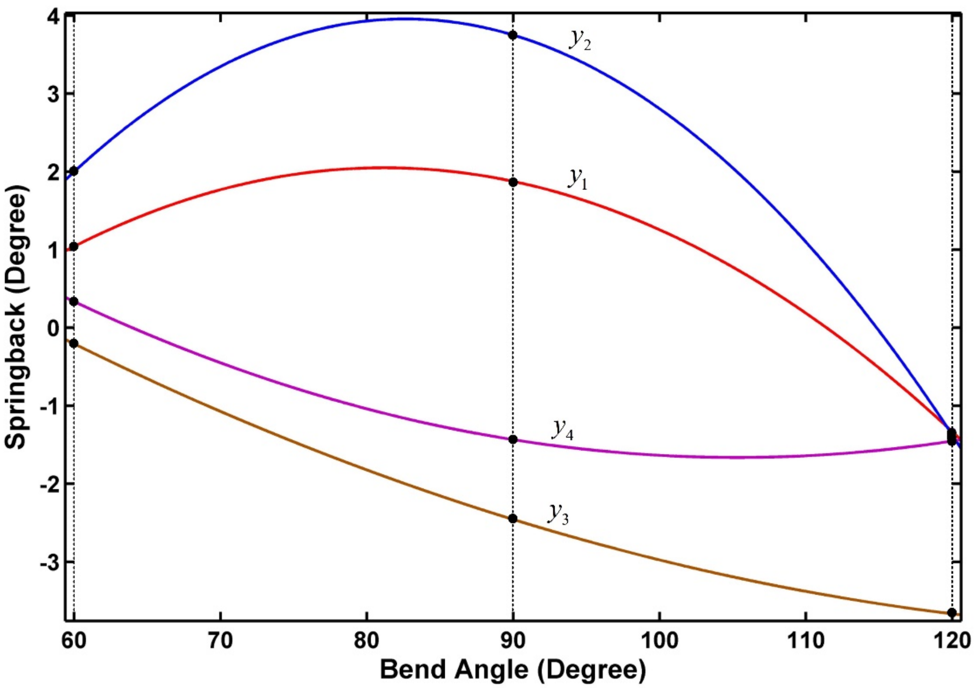

Figure 8. Fitted curves for the prediction of springback in JSH440 sheet metal.

Since the magnitude of springback is essential to the analysis here, hence absolute springback is minimized. Optimization has been applied for different types of blank geometry to obtain optimal machine tool process parameters for the minimum springback in the JSH440 sheet metals. The objective of the optimization is to determine the optimal process parameters for several blanks having different geometries. The following objective function represents the optimization problem:

$$z = min\ |Springback(T, W, A, L, H)| \tag{6}$$

subjected to

$$T = 1.4, 1.6 \tag{7}$$

$$W = 20, 50 \tag{8}$$

$$A = 60, 90, 120 \tag{9}$$

$$0 \le L \le 180 \tag{10}$$

$$0 \le H \le 10 \tag{11}$$

A program has been written in MATLAB to apply the Genetic Algorithm (GA) over the optimization. The parameters of the optimizations are set as shown in Table 5 (MATLAB, 2020), whereas the optimal values of the process parameters for the minimum springback are shown in Table 6.

Table 5. Parameters for Genetic Algorithm (GA).

Parameter	**Value**
Populations size	200
Cross-over fraction	0.7
Elite count	10
Fitness scaling	Rank-wise
Lower bound	[30,0]
Upper bound	[180,10]
Mutation and cross-over functions	Constraint dependent

Table 6. Optimal applied load and holding time for the minimum springback.

Thickness (mm)	Width (mm)	Bend Angle (Degree)	Applied Load | ($kgcm^{-2}$)	Holding Time (sec)	Minimum Springback (Degree)
1.4	20	30	30	10	0.245
1.4	50	30	30	10	1.389
1.4	20	45	30	10	0.859
1.4	50	45	30	10	2.184
1.4	20	60	30	10	1.203
1.4	50	60	30	10	2.708
1.6	20	30	127.661	4.033	0.000
1.6	50	30	84.789	4.987	0.000
1.6	20	45	132.67	8.915	0.000
1.6	50	45	39.521	8.695	0.000
1.6	20	60	114.489	6.537	0.000
1.6	50	60	30	10	0.287

Few optimal values of springback are still higher such as in the case of a 1.4mm thick sheet, where the minimum springback attained is 2.184 or 2.708. It is due to the springback regression model limitation, which cannot provide a lesser springback magnitude. Hence, the limitation of the springback model provided in the research is that it cannot optimize springback up to zero in JSH440 sheet metals for the thickness of 1.4mm. It successfully optimizes the springback up to zero magnitudes in most cases of thickness 1.6mm.

CONCLUSION

In contrast to the analytical and generic models of springback for the carbon steel sheets, JSH440 exhibits positive and negative springback. Based on the data gathered, analysis, and inference, the following results can be inference.

Springback in JSH440 sheet metals are significantly influenced by the geometrical parameters of the blank, which are thickness, bend angle, and width, in order of their significance.

- Springback versus thickness shows that springback directly relates to the thickness in the banks having the width of 20mm, whereas it decreases with the thickness in strips having higher width if bent to acute and right angles. A slight discrepancy to this behaviour is seen in the sheet metals bent to 120°. It occurred due to the bends' increased area, which stores more residual stress and causes higher springback.

- Springback is usually directly proportional to the width, especially in the sheet metal bent to acute angles, whereas it shows a reverse behaviour in the strips bent to an obtuse angle. It can also be inferred from the analysis that the sheet metal bent to 90° has a neutral effect in JSH440 sheet metals, where the behaviour of springback varies from negative to positive springback.
- Bent angle to springback relation shows that the highest springback is observed in the JSH440 sheet metals blanks when bent to 90°. The highest springback magnitude is positive. That is, the elastic recovery of the sheet metals increases the bend angle. In most of the sheet metals bent to 60°, positive springback has been observed, whereas, in the strips bent to 120°, negative springback is recorded generally. The highest magnitude of springback is seen in the JSH440 blanks having a width of 50mm.
- ANOVA results show that applied load has no significant influence over the springback in blanks of JSH440. However, a slight decrease in springback has been observed by increasing the applied load in the strips bent to 120°.
- Unlike the springback in other Carbons Steels, ANOVA and graphical analysis show an insignificant influence of the holding time over the springback.
- It can be seen from ANOVA that the interaction of controllable factors has little influence over the springback.
- Analytical models of springback in JSH440 have been presented. Eq. 1 presents an overall springback analytical model to determine the springback in JSH440 sheet metals. Specific quadratic equations for the prediction of springback in various geometries of JSH440 blanks are also presented.
- Finally, optimized machine tool parameters are presented for the minimum springback in the JSH440 sheet metals. A genetic algorithm has been used to optimize the process parameters. It shows the minimum springback in different blank geometries, which can be achieved through the optimal applied load and holding time.

Experimental investigation and analytical results state that hot-rolled, high-tensile strength sheet metals possess entirely different behaviours than traditional carbons steels. Negative and positive springback are present in these sheet metals during the v-bending process, which can be predicted using the analytical model presented in this article.

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