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Experimental comparison of straight flanging and rotary die bending based on springback

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Abstract

Springback in sheet bending is a well-defined phenomenon; however, variation of springback is difficult to control causing quality problems in especially mass-produced goods such as home appliances. As an alternative to straight flanging, the rotary die bending process offers reduced springback as well as reduced geometric variation; however, there is little knowledge in the literature. The effects of process parameters on the springback behavior of straight flanging and rotary die bending as applied to home appliance side panels are investigated experimentally. For each flange bending method, effects of die radius, punch-die clearance, rolling direction, flange length, and material supplier on springback are tested on EN DC01 carbon and SAE 430 stainless steel sheets. A material-wise factorial experimental design was applied to investigate the factor interactions as well as the main effects using ANOVA. In both methods, die radius was the most dominant factor on springback, clearance being the second, and the inevitable material property variations being the third one. Nevertheless, in rotary die bending, springback values were smaller with significantly less scatter compared to straight flanging. Consequently, rotary die bending is a much more preferable process especially in mass production performed with narrow profit margins.

Keywords Straight flanging · Rotary die bending · Springback

1 Background and objectives

The most commonly used manufacturing method in the production of body panels in the home-appliance industry is bending. Various problems can be encountered in bending caused by both material and process parameters. The dimensional errors are one of the most important of these problems, and they generally originate from springback.

Several methods are introduced to minimize the springback and its effects on final part geometry. These methods are over-bending, bending with coining, bending in tension, reverse bending, etc. The amount of springback after bending must be predicted, and the effects of sheet metal properties and process parameters on springback must be well

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known to compensate for the springback by over-bending. Through this explanation, it can be said that material properties such as elastic modulus, yield strength, and anisotropy and forming process parameters including die radius and punch-die clearance affect springback. Springback also depends on the bending method. Air bending, V-die bending, straight flanging, and rotary die bending give different springback characteristics for the same material. The springback problems, particularly its variation, can cause substantial financial losses in the production involving sheet metal forming. The expense of springback problems due to production delays, tool replacement costs, rejected scrap materials, etc., was reported to exceed \$50 million annually in the United States automotive industry [1].

When the applied load is removed after forming the metal sheet, the material tends to recover elastically and return to its original form [2]. Springback can be defined as the elastic recovery that results after getting rid of the bending moment during forming [3]. Besides, springback is the dispersion of the forming stresses in the material, met after the forming dies are removed, and thus, residual stresses are encountered [4, 5]. As the induced forming stresses increase, the springback also increases [6].

Springback is a forming problem where multiple interactions of many variables including mechanical properties, process parameters, and dimensional factors are involved. Process parameters and mechanical properties interact and generate the stress distribution through the sheet thickness that will affect springback [7]. These effects make springback estimation and compensation difficult. Therefore, to make a healthy analysis, factor interactions must be taken into account besides the mean effects [8].

Independent of the bending type, the amount of springback increases with the ratio of bending radius to sheet material thickness [2, 9, 10]. As the sheet material thickness (t) decreases or the r/t ratio increases, the springback angle monotonically increases [11–13]. In a recent paper by Wang et al. [14], it was again shown that with decreasing r/t ratio, the springback ratio decreases gradually. As a result of the increased thickness, the residual stresses encountered in the bending zone decrease.

Clearance between the punch and die is generally selected 1.1 times the sheet thickness, considering the thickness tolerance of 10% in cold-rolled sheet metal. Springback monotonically increases as the clearance increases because the clearance dictates the conforming of the sheet to the die [15]. Ling et al. [16] stated that this tendency becomes less visible as the die radius increases from 0.5t to 3.0t. With the narrowing of the die clearance, plastic deformation in the bending zone is localized and intensified decreasing the springback [12].

The elastic modulus is the most influential material property on the springback. A higher elastic modulus leads to smaller elastic deformation at the bending zone, and thus less springback [17]. Since bending is an elastic–plastic deformation, yield strength or plastic flow stress is also very influential because along with Young's modulus, it determines the elastic resilience [2]. Sun and Lang [18] showed again that with increasing elastic modulus springback decreased, and with increasing yield strength springback increased. Increasing the strain hardening coefficient (n) in Hollomon's rigid plastic model also increases the elastic strain component in the total bending strain, and thus the springback [19].

A significant amount of work is published on industrially standard bending methods. Among them, numerous papers focus on straight flanging, some being experimental as well as numerical [12, 15, 20–23]. Numerical work is mostly on finite element prediction of springback. However, literature on the rotary die bending process is very weak.

The oldest and most common method used in forming refrigerator doors and side panels from sheet metal is straight flanging. The schematic representation of this process is given in Fig. 1. The purpose of this process is to obtain a 90° bent flange mostly. In straight flanging,



Fig. 1 Straight flanging process

the punch performs a linear motion similar to the V-die bending and air bending processes. However, unlike the other methods, the bending process takes place around the bending die, not around the punch tip. Throughout the linear movement of the punch, the position of the contact segment between the punch and the sheet changes continuously. This motion continues until bending is complete. Here, the entire movement of the punch on the bending edge can be called wiping die bending. Critical process parameters are the die (bending) radius (R_d), blank thickness (t), clearance between the punch and die (c), the flange length (L_f), and the blank-holder (pressure pad) force (F_{bh}) [24].

Another method of bending box-type parts in the home appliance industry is rotary die bending (Fig. 2). In this process, the upper die, called the rocker, replaces the punch [25]. Instead of the linear movement made by a solid punch, the rocker rotates during the downward linear motion. With the help of this rotation, the flange is locally bent around the die shoulder. Similar to straight flanging, sometimes, it is possible to use a blank-holder but in general, a blank-holder is not used in this process. This simplification is an advantage of the process in the industrial environment.

In this article, the springback effects in flanging using a solid punch and a rotary die are experimentally compared on cold-rolled carbon and stainless-steel sheets. The factors tested under material variability faced in the industrial environment were the die radius, punch-die clearance, bending axis with respect to rolling, and flange length.





Fig. 2 The rotary die bending process

2 Experimental design

2.1 Materials

EN DC01 low carbon steel and SAE 430 stainless steel were used in the experiments being the most common sheet steels used by the home appliance industry. DC01 sheets were obtained from two, and SAE 430 sheets were from three different suppliers so that the effect of material variability could be investigated. The measured chemical compositions of the materials are given in Table 1. The thickness of all the samples was 0.5 mm, except that of SAE 430 #3 was 0.6 mm. The mechanical properties were obtained by tensile tests repeated five times (Table 2). Accordingly, there is more variation among the mechanical properties of DC01 samples in different batches compared to the SAE 430 samples.

2.2 Experimental plan

The investigated parameters and their levels are listed in Table 3. Except for the flange length, all parameters had two levels. The specimen width was 100 mm to ensure the plane strain conditions. Experiments were grouped according to the bending method and materials, as shown in Tables 4 and 5. The material-wise factorial DOE matrix was applied for each material. All tests were repeated twice. Consequently, 96 and 72 tests were conducted for straight flanging and rotary bending, respectively.

In straight flanging tests, tests both 0.5 and 2.0 mm die radii were used. However, only a 2.0 mm die radius was possible in rotary flanging. This is because of the process limitation that the die radius must be concentric with the rotation arc of the rocker for the bending process to be performed correctly. When the die with a 0.5-mm shoulder radius was

Table 1	Chemical	compositions
of the sa	ample mat	erials

Weight %	t [mm]	%Fe	%C	%Si	%Mn	%Cr	%Ni	%Cu	%Ti	%Al	%V	%W
DC01 #1	0.5	99.5	0.032	0.021	0.18	0.022	0.011	0.025	0.002	0.051	0.004	0.04
DC01 #2	0.5	99.6	0.015	0.005	0.156	0.005	0.057	0.059	0.002	0.076	0.002	0.04
SAE 430 #1	0.5	82.5	0.069	0.305	0.466	16.4	0.062	0.087	0.005	0.005	0.017	0.02
SAE 430 #2	0.5	82.5	0.066	0.333	0.465	16.4	0.064	0.088	0.005	0.005	0.019	0.02
SAE 430 #3	0.6	82.7	0.049	0.246	0.247	16.2	0.138	0.213	0.005	0.006	0.09	0.02

Material name	Measured thickness [mm]	Yield strength (Sy) [MPa]	Tensile strength (Su) [MPa]	Uniform elongation [%]	Elongation at rupture [%]	Strain hardening exponent	Strength coefficient [MPa]
DC01 #1-RD	0.5	246	342	19	27	0.21	594
DC01 #1-TD	0.5	243	338	19	25	0.2	580
DC01 #2-RD	0.5	277	355	21	31	0.2	604
DC01 #2-TD	0.5	284	356	19	26	0.2	605
SAE 430 #1-RD	0.5	307	479	23	31	0.3	974
SAE 430 #1-TD	0.5	318	487	22	29	0.28	959
SAE 430 #2-RD	0.5	302	472	23	32	0.28	915
SAE 430 #2-TD	0.5	319	484	22	30	0.27	924
SAE 430 #3-RD	0.6	313	479	21	27	0.26	912
SAE 430 #3-TD	0.6	340	499	19	26	0.25	926

Table 2	Mechanical pro	perties of DC01	and SAE 430 sam	ples used in the ex	periments (RD	orolling direct	tion, TD transverse directio	n)
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 Table 3 Investigated parameters and their levels

	Parameters
Method	Straight flanging, rotary die bending
Material	DC01 Drawing Quality Carbon Steel, SAE 430 Ferritic Stainless Steel
Bending radius	0.5, 2 mm
Die clearance	0.1, 0.2 mm
Rolling direction	Rolling direction (RD), transverse direction (TD)
Flange length	20, 30, 40 mm

used, adjusting the concentricity would not be possible. Therefore, a fixed 2-mm bending radius could be used in the rotary bending tests. Nevertheless, the springback and its variation are larger at 2.0 mm R_d , and using a single value for it still gave sufficiently meaningful results.

The SAE 430 #3 was different from all the other samples with 0.6 mm thickness; therefore, two separate test sets were designed for that (Table 5). This can be considered a verification test to see if the generalizations derived at constant thickness are valid for 20% larger thickness. SAE 430 #3 had very close mechanical (tensile) properties compared to the other two stainless steel sheets; however, there are some minor differences in chemical composition. It has 26% less C and Si, while the Ni content is twice as much. Although the ratios of these alloying elements are very small, especially Ni may have some effect on elastic–plastic behavior.

Flange length may vary as a product design parameter, and the nonlinearity effect of flange length was tested on both DC01 #2 and SAE 430 #3 samples. Similarly, the effect of rolling direction to spring back was also tested using the tests on these samples.

Table 4The material-wisefactorial DOE matrix appliedon the sheets with 0.5 mmthickness

Material	Method	Geometric parameters of experiments						
		Bending radius (mm)	Die clearance (mm)	Flange length (mm)	Bending axis direction			
DC01 #1 SAE 430 #1	Straight flanging	0.5, 2	0.1, 0.2	20, 40	RD			
SAE 430 #2								
DC01 #1 SAE 430 #1	Rotary die bending	2	0.1, 0.2	20, 40	RD			
DC01 #2	Straight flanging Rotary die bending	0.5, 2 2	0.1, 0.2 0.1, 0.2	20, 30, 40 20, 30, 40	RD, TD RD, TD			

Table 5 Matrix of additionalexperiments conducted on SAE430 #3 (t=0.6 mm)

Method	Geometric parameters of experiments							
	Bending radius (mm)	Die clearance (mm)	Flange length (mm)	Bending axis direction				
Straight flanging	0.5, 2	0.1, 0.2	20, 30, 40	RD, TD				
Rotary die bending	2	0.1, 0.2	20, 30, 40	RD, TD				

2.3 Experimental apparatus

An experimental apparatus was designed, as seen in Fig. 3. After the steel sheet to be bent was compressed by the blank-holder, the punch moved vertically and performed the bending process. The blank-holder was supported by two nitrogen cylinders (with a maximum pressure of 100 bars) that acted as springs. The punch-die clearance was adjusted by placing shims with different thicknesses behind the bending die. The rotary die bending process

Fig. 3 Straight flanging test setup



was conducted in the experimental setup shown in Fig. 4. Nitrogen cylinders were used again to apply the blankholder force. After the sheet is compressed by the blankholder, the rocker die is moved vertically and applied to the bending operation. Here, the linear motion of the punch turns into a circular motion on the rotating die. For the bending process to be performed correctly, the bending die radius is provided to be as concentric as possible with the rotation performed by the rocker. Therefore, a fixed 2-mm bending radius is used in the rotary bending tests. All experiments were conducted in dry conditions to simulate the actual process applied in the industry. The effect of friction on springback in-plane strain bending is considered negligible in the literature. Tools were machined by end milling and the surface roughness is about 0.8 μ m.

After the experiments were conducted, the angle after unloading was measured using a coordinate measurement machine (CMM). On the CMM, a line passing (approximately) through three points on the flange was defined, and the angle between this line and the ground plane was calculated. This measurement is performed in three different positions on each sample (Fig. 5). The adequacy analysis of the measurement system was performed, and it was found that the system variability was 0.02% of the total variability. Thus, the part-to-part variability is larger



Fig. 5 Measured points on a bent specimen

than the measuring system variability. When the results were statistically analyzed, the p value was found smaller



Fig. 4 Rotary die bending test setup

than 0.05. Hence, it was concluded that variation of the measured values is statistically significant.

3 Results and discussions

3.1 Straight flanging

Experimental results were analyzed using the Minitab v.19 program, and main effect and interaction plots, as well as ANOVA tables, were obtained. The main effect plots of straight flanging are shown in Fig. 6 for the SAE 430 #1 (Sy, Yield strength: 307 MPa) and #2 (Sy 302 MPa). Accordingly and as expected, directly proportional effects of bending (die) radius and clearance can be observed, while flange length has no effect within the constraints applied. Contribution ratios of the factors and p values were given in Table 6. Accordingly, the effect of the bending radius is in the first order, with 69% and 59%. While the impact of die clearance is 15–20%, the effect of flange length is below 1%. The p values below 0.05 show the statistical significance of the factors.

Interaction plots of tests on SAE 430 #1 and #2 are given in Fig. 7 side by side. The interaction between the die clearance and die radius clearly shows that die clearance has no effect when the smaller die radius was used. However, for a larger die radius, clearance has a visible effect. When the die clearance is increased from 0.1 to 0.2 mm (for R_d 2.0 mm), an average increase of 2.7% is encountered in springback. At die radius 2.0 mm, the springback varies between 3.4 and 6.6%. When the die radius is small, the actual bending radius is very close to that anyway, but when the die radius is larger, actual bending radius gets significantly larger with increased clearance. Similarly increased flange length also improves conformity to the die shoulder and helps to produce a sharper edge. However, within the tested range, no clear effect of flange length could be observed according to the plots of SAE 430 #1.

SAE 430 #1 SAE 430 #2 Factors Contribution Contribution p value p value Bending radius 59.58% 69.09% 0.000 0.000 (mm) Die clearance 15 68% 0.000 18.01% 0.000 (mm)Flange length 0.67% 0.066 0.29% 0.277 (mm) Bending 13.33% 0.000 19.72% 0.000 radius × die clearance (mm) Error 1.23% 2.40% Lack-of-fit 0.33% 0.449 1.67% 0.018 Pure error 0.90% 0.73% Total 100.00% 100.00%

Table 6 Contribution ratios and p values of the factors on springback

in straight flanging as outputs ANOVA using Minitab

The straight flanging experiments were separately conducted for SAE 430 #3 (Sy 313 MPa, t 0.6 mm) at three flange lengths and two directions besides two levels of die radius and clearance for validation and generalization purposes. It is again shown that only the die radius has the most significant effect on springback, as shown in Fig. 8. According to the interaction plot on the right, it was verified that flange length does not affect the springback significantly, and no visible interactions take place with other factors. Similarly, the rolling direction does not have a significant effect on springback either. Although the yield strength varies depending on the rolling direction, the grain distribution displays a homogeneous distribution in parallel and transverse rolling directions (Fig. 9). When the die radius is 2.0 mm, the amount of springback varies between 3.0 and 3.8%. This result showed that slightly thicker material (0.6 mm) SAE 430 #3 was affected by process conditions less than the thinner two SAE 430 variants in straight flanging.



Fig. 6 Main effect plots for straight flanging of SAE 430 #1 (left) and #2 (right)



Fig. 7 Interaction plots for straight flanging of SAE 430 #1 (left) and #2 (right)



Fig. 8 Main effect (left) and interaction plots (right) for straight flanging of SAE 430 #3 (with 0.6 mm thickness)



Fig. 9 Grain distribution of SAE 430 #3 material at parallel (a) and transverse (b) rolling directions

The parameters that have significant effects on straight flanging of DC01 #1 (Sy 246 MPa) are the die radius and clearance with contribution ratios of 63% and 34%, respectively (Fig. 10). However, for higher strength variant DC01 #2 (Sy 277 MPa), the effect of the die radius is higher at 89%, while the impact of flange length is insignificant at 0.74%. When the die radius is 2.0 mm, the springback varied between 3.7 and 7.3% for DC01 #1 (Sy 246 MPa), and the same variation was between 4.0 and 6.9% for DC01 #2 (Sy 277 MPa). Besides, the rolling direction did not show a direct effect on springback again, because the grain distribution was dominantly homogeneous in the directions parallel and transverse to rolling (similar to Fig. 9).

The most effective parameter in the straight flanging process is the die (shoulder) radius for all tested materials because it imposes the bending radius directly. The springback is significantly higher, at the larger die radius (2.0 mm). Besides, at a higher die radius, the effects of other parameters on the springback are more pronounced than that with the smaller one (0.5 mm). In all mathematical models, springback angle after bending is directly proportional to R/t ratio either it is small or large [1, 12, 26, 27]. The total strain increases monotonically from neutral radius towards the outer edge of the cross-section. With the increase of the bending radius (in proportion to material thickness), the maximum strain, and thus plastic stress encountered on the outer edge (bend surface) decreases. With the decrease of total (elastic + plastic) strain and stress over the material cross-section at larger R/t ratio, the reversible elastic deformation becomes more dominant, and it causes more recovery in geometry when the applied forming load is removed.

3.2 Rotary die bending

In the rotary die bending process, it was found that changing clearance and flange length was not statistically

 Table 7
 ANOVA table for SAE 430 #2 in rotary die bending test results

Factor	DOF	Sum of squares	Contribution	F value	p value
Die clearance (mm)	1	0.090601	84.34%	62.74	0.02
Flange length (mm)	1	0.015376	14.31%	10.65	0.189
Error	1	0.001444	1.34%		
Total	3	0.104421	100.00%		

meaningful for SAE 430 #1 (Sy 307 MPa) as the p values were not less than 0.05. In the ANOVA table, the effect of the parameters was determined by contribution which is the ratio of each parameter's sum of squares to the total sum of squares. The clearance was found to be statistically significant for SAE 430 #2 (Sy 302 MPa) and #3 (Sy 313 MPa and t 0.6 mm) with p values of 0.02 and 0, respectively (Table 7). The main effect plots of the parameters are given in Fig. 11. Again, it was found that only die clearance is active on springback for DC01 #1 and #2 with contribution ratios of 68.5% and 76.1%, respectively. The main effect plot of the samples is given in Fig. 12. In the rotary die bending process, as the die clearance increases, the material does not completely form around the radius and exhibits the behavior encountered with a large radius value. At this point, it can be said that the amount of plastic deformation encountered within the material has decreased. This reduction in plastic deformation causes more recovery in the material after removing the load applied during forming. Since the die radius is constant as a constraint of the die design, the effect of the die (bending) radius on the springback could not be investigated in the rotary die bending process.



Fig. 10 Main effect plots for straight flanging of DC01 #1 (left) and #2 (right)



Fig. 11 Main effect plots for rotary die bending of SAE 430 #2 (t 0.5 mm) (left) and #3 (t 0.6 mm) (right)

Although it was found that die clearance is active in the process, its effect is not as high as in straight flanging. As the die clearance increases when the bending radius was 2 mm, an increase in the amount of springback and its amount range were given in Table 8. The effect of an increase in the die clearance is more pronounced for the straight flanging process. In straight flanging, there is an average of 2.6% depending on the parameters, while in the rotary die bending process, this range is 0.6% on average. Rotary die bending results in less springback. The reason for less springback is that the rocker applies higher pressure on the die shoulder. This causes the wrapping of the blank over the die more precisely, so the springback values decrease in rotary die bending.

Another result obtained from the experiments is that the increase in the blank thickness affects the springback behavior. The thickness of SAE 430 #1 and #2 was 0.5 mm, while the thickness of SAE 430 #3 was 0.6 mm. According to Table 8, the springback angles for SAE 430 #3 sheets are lower in both processes and the springback range is narrower, especially in rotary die bending. This proved the well-known sensitivity of the bending processes to blank thickness.

The different behaviors of the materials show that the effect of material variations, including the one in chemical composition, cannot be neglected. Thus, it should not be ignored that a material supplied from different producers or even provided from various parties from the same supplier may exhibit different behavior in the bending process under the same conditions.

The comparison of angle measurements for both processes at a die clearance of 0.2 mm is given in Fig. 13. As can be seen from the plot, the rotary die bending process produced consistently smaller springback angles. Although it was found that die clearance is effective in the process, its effect is not as high as in straight flanging (Table 7 and Fig. 13). The effect of an increase in the die clearance is



Fig. 12 Main effect plots for rotary die bending of DC01 #1 (left) and #2 (right) (t 0.5 mm and R_d 2.0 mm)

Table 8 The increase in springback and its ranges as a function of die clearance (die radius 2 mm)

Material	Increase in springba	ack	Springback range			
	Straight flanging	Rotary die bending	Straight flanging	Rotary die bending		
DC01 #1	2.8%	0.4%	3.7-7.3%	3.1-3.7%		
DC01 #2	No clear effect	0.7%	4.0-6.9%	2.7-3.5%		
SAE 430 #1	2.4%	0.2%	3.4-6.0%	3.7-4.4%		
SAE 430 #2	2.7%	0.4%	3.4-6.6%	4.0-4.7%		
SAE 430 #3	No clear effect	0.3%	3.0–3.8%	3.1–3.7%		

more pronounced for the straight flanging process. Rotary die bending results in less overall springback. The reason for less springback is that the sheet pushed by the rocker applies higher pressure on the die shoulder, and the wrapping of the blank over the die shoulder is more precise, so the springback values are relatively less in rotary die bending.

Average angles after springback and their variance for each process are shown in Fig. 14. The average variation in straight flanging was 1.23° and it is 0.11° in rotary die bending. Compared to straight flanging, the average springback angles in rotary die bending were 40% and 13% less in DC01 and SAE 430 samples, respectively. Consequently, it is proven that rotary die bending is advantageous in reduced variation as well as reduced angle after springback, and thus, it is a more robust process in the manufacturing of box-type parts and panels and other industrial applications.

When the springback versus yield strength plots are compared, straight flanging gave consistently higher springback angles within the tested range (Fig. 15). Besides, it is seen that straight flanging is less sensitive to yield strength variation compared to rotary die bending. It is probably due to the wiping effect of the punch with a very small clearance. Therefore, small yield strength

springback for all samples

2 mm

variations in the incoming sheet steels in the production environment should not be much of a concern, and thus, the die parameters die radius and clearance should be kept under strict control to maintain a controlled springback behavior. On the other hand, in rotary die bending, an operation closer to pure bending (like a simply supported beam loaded between the supports) is performed, and thus, the final springback is more susceptible to yield strength variations. The average springback of stainless-steel specimens is + 1.1% higher than those of the carbon steel ones. The batch-to-batch variations in both materials are in the same range, and rotary die bending absorbs these variations effectively.

Plane strain sheet bending was modeled using analytical, semi-empirical and numerical methods extensively [26]. Predictions of these models were also validated by some experimental data [11, 12]. The straight flanging process and springback have been elaborated extensively. When a bending process such as flanging is modeled with a minimalist approach, the simple bending model is the choice. Accordingly, the die (shoulder, corner) radius-to-thickness ratio is the major variable determining the springback in addition to the material parameters (including the elastic modulus and yield strength). In the







industrial process of straight flanging, other factors including punch (nose) radius, punch-die clearance, flange length, and pad (blank-holder) force also come into the picture. These variables determine the conforming of the sheet to the die and thus the actual bending radius. Besides, the effect of friction is dictated by the clearance in interaction with flange length. According to the springback measurements after straight flanging, conforming of the sheet to the die radius is less than it is in rotary die bending, and eventually, the actual bending radius is larger than the die radius. Hence, the average springback in straight flanging is larger than rotary die bending.

The kinematics of the rotary die bending is different than flanging such that the rocker motion generates improved conformity of the sheet to the die shoulder and thus the actual bending radius is equal or very close to the die radius. Consequently, less springback occurs. Besides, the wrapping effect on the sheet produced by the rocker turns out to be very consistent such that variation in springback angle is also significantly reduced. The larger span of springback in straight flanging may be due to small variations in friction conditions during the wiping motion of the punch. There is a wiping motion of the rocker in rotary die bending as well. However, the rocker pushes the sheet towards the die wall improving the wrapping and thus the sheet conforms to the die profile very closely and consistently.



Fig. 15 Mechanical property (yield strength) based main effects for straight flanging and rotary die bending (R_d 2 mm, t 0.5 mm)

4 Concluding remarks

In this article, the effects of straight flanging and rotary die bending on springback are investigated using the design of experiments approach and ANOVA. In the tests, EN DC01 carbon steel and SAE 430 ferritic stainless-steel sheets were used in five batches. The thickness, chemical composition, and mechanical properties of the materials were measured before the bending tests. Parameters included in the experiments were the die radius, die clearance, flange length, and rolling direction as well as material variations. Statistical analyses were conducted on springback angles, and the following conclusions can be summarized:

- In straight flanging, die radius was the most dominant factor on springback, clearance being the second, and the inevitable material property variations being the third.
- Die clearance was the dominant factor while yield strength followed that in rotary die bending where a fixed die radius was tested. Flange length did not show a strong influence.
- The average springback angle in rotary die bending compared to straight flanging is 40% less for DC01, and 13% less for SAE 430.
- The springback angle scatters encountered in rotary die bending were significantly narrower (0.6%) compared to straight flanging (2.6%).
- Steel sheets from different suppliers or in various parties from the same supplier may cause springback angle variation under constant straight flanging process conditions; however, rotary die bending covers that problem effectively by reducing the average variation in the springback angle from 1.23° to 0.11°.
- Examining the microstructure of both DC01 and SAE 430 specimens, a homogeneous grain structure was observed in both directions, and thus, the rolling direction does not affect springback in these materials.

It can be concluded that rotary die bending achieves a consistently better conforming of the sheet to the die shoulder and yields less springback with smaller scatter than straight flanging in the tested working range. Therefore, the rotary die bending method is a more appropriate choice in the mass production of box-type parts and to keep the geometric deviations to the lowest level.

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Declarations

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References

- Gan W, Wagoner RH (2004) Die design method for sheet springback. Int J Mech Sci 46:1097–1113. https://doi.org/10.1016/j. ijmecsci.2004.06.006
- Tekiner Z (2004) An experimental study on the examination of springback of sheet metals with several thicknesses and properties in bending dies. J Mater Process Technol 145:109–117. https:// doi.org/10.1016/j.jmatprotec.2003.07.005
- Yi HK, Kim DW, Van Tyne CJ, Moon YH (2008) Analytical prediction of springback based on residual differential strain during sheet metal bending. Proc Inst Mech Eng Part C J Mech Eng Sci 222:117–129. https://doi.org/10.1243/09544062JMES682
- Lazim D (2004) Springback in draw-bending on aerospace alloys. Dissertation, McGill University
- Zhang DJ, Cui ZS, Chen ZY, Ruan XY (2007) An analytical model for predicting sheet springback after V-bending. J Zhejiang Univ Sci A 8:237–244. https://doi.org/10.1631/jzus.2007.A0237
- Chen F-K, Ko S-F (2006) Deformation analysis of springback in L-bending of sheet metal. J Achiev Mater Manuf Eng 18:339–342. https://doi.org/10.1166/asl.2011.1713
- Chen P, Koç M (2007) Simulation of springback variation in forming of advanced high strength steels. J Mater Process Technol 190:189–198. https://doi.org/10.1016/j.jmatprotec.2007.02.046
- Wei L, Yuying Y, Zhongwen X, Lihong Z (2009) Springback control of sheet metal forming based on the response-surface method and multi-objective genetic algorithm. Mater Sci Eng A 499:325–328. https://doi.org/10.1016/j.msea.2007.11.121
- 9. Gau J-T (1999) A study of the influence of the Bauschinger effect on springback in two-dimensional sheet metal forming. Dissertation, The Ohio State University
- Kim HS, Koç M (2008) Numerical investigations on springback characteristics of aluminum sheet metal alloys in warm forming conditions. J Mater Process Technol 204:370–383. https://doi.org/ 10.1016/j.jmatprotec.2007.11.059
- Müderrisoğlu A, Livatyalı H, Ahmetoğlu M, Akgerman N, Altan T (1997) Bending, flanging and hemming of aluminum and steel sheets progress report I. Engineering Research Center for Net Shape Manufacturing, ABC/ERC/NSM-97-R015, The Ohio State University, Columbus OH
- Livatyali H, Altan T (2001) Prediction and elimination of springback in straight flanging using computer-aided design methods: Part 1. Experimental investigations J Mater Process Technol 117:262–268. https://doi.org/10.1016/S0924-0136(01)01164-5

- Garcia-Romeu ML, Ciurana J, Ferrer I (2007) Springback determination of sheet metals in an air bending process based on an experimental work. J Mater Process Technol 191:174–177. https:// doi.org/10.1016/j.jmatprotec.2007.03.019
- Wang A, Xue H, Saud S, Saud S, Yang Y, Wei Y (2019) Improvement of springback prediction accuracy for Z-section profiles in the four-roll bending process considering neutral layer shift. J Manuf Process 48:218–227. https://doi.org/10.1016/j.jmapro. 2019.11.008
- Mkaddem A, Saidane D (2007) Experimental approach and RSM procedure on the examination of springback in wiping-die bending processes. J Mater Process Technol 189:325–333. https://doi.org/ 10.1016/j.jmatprotec.2007.02.004
- Ling YE, Lee HP, Cheok BT (2005) Finite element analysis of springback in L-bending of sheet metal. J Mater Process Technol 168:296–302. https://doi.org/10.1016/j.jmatprotec.2005.02.236
- Zajkani A, Hajbarati H (2017) Investigation of the variable elastic unloading modulus coupled with nonlinear kinematic hardening in springback measuring of advanced high-strength steel in U-shaped process. J Manuf Process 25:391–401. https://doi.org/ 10.1016/j.jmapro.2016.12.022
- Sun Z, Lang L (2017) Effect of stress distribution on springback in hydroforming process. Int J Adv Manuf Technol 93:2773–2782. https://doi.org/10.1007/s00170-017-0670-x
- Kim H, Chatti S, Kardes N (2012) Bending, flanging, and hemming. In: Altan T, Tekkaya AE (eds) Sheet Metal Forming. Processes and applications. ASM International 19–33
- Kazan R, Firat M, Tiryaki AE (2009) Prediction of springback in wipe-bending process of sheet metal using neural network. Mater Des 30:418–423. https://doi.org/10.1016/j.matdes.2008.05.033

- Chen L, Chen H, Guo W et al (2014) Experimental and simulation studies of springback in rubber forming using aluminium sheet straight flanging process. Mater Des 54:354–360. https://doi.org/ 10.1016/j.matdes.2013.08.050
- Han K, Li X, Peng X et al (2019) Experimental and numerical study on the deformation mechanism of straight flanging by incremental sheet forming. Int J Mech Sci 160:75–89. https://doi.org/ 10.1016/j.ijmecsci.2019.06.024
- Chen C, Gong J, Chen Y et al (2021) A prediction model for bending springback of AZM120 sheet metal and mechanical compensation of CNC automatic panel bender. Int J Adv Manuf Technol 116:3325–3337. https://doi.org/10.1007/s00170-021-07606-1
- Gürgen S (2019) Numerical modeling of roller hemming operation on a straight edge part. J Braz Soc Mech Sci Eng 41:512. https:// doi.org/10.1007/s40430-019-2030-2
- Wasif M, Iqbal SA, Tufail M et al (2020) Experimental analysis and prediction of springback in v-bending process of high-tensile strength steels. Trans Indian Inst Met 73:285–300. https://doi.org/ 10.1007/s12666-019-01843-5
- Livatyali H, Kinzel GL, Altan T (2003) Computer-aided die design of Straight flanging using approximate numerical analysis. J Mater Process Technol 142–2:532–543. https://doi.org/10.1016/ S0924-0136(03)00655-1
- 27. Dametew AV, Gebresenbet T (2017) Study the effects of spring back on sheet metal bending using mathematical methods. J Material Sci Eng 6:382. https://doi.org/10.4172/2169-0022.1000382

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