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 full 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.

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 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, anisotropy, etc., and forming process parameters including die radius, punch-die clearance, etc., 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 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 decreases.

Clearance between the punch and die is generally selected 1.1 times the sheet thickness, considering the thickness tolerance of %10. 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]. Increasing the strain hardening coefficient (n) also increases the elastic strain component in the total bending strain, and thus the springback [18].

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, 19, 20, 21]. 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, 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 or wipe 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}).

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. 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.

Rotary die bending can be used to decrease the springback of the parts according to straight flanging. Besides, it is more robust to process variation. However, the literature on the rotary die bending process is inadequate. 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.

2. Experimental Design

2.1. Materials

In the experiments, EN DC01 low carbon steel, and SAE 430 stainless steel were used. DC01 sheets were from two, and SAE 430 sheets were from three different suppliers so that the effect of material variability was could be investigated. The chemical compositions of the materials are given in Table 1. Hence, 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

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 Table 4. Full-factorial experiments were performed in each group. All tests were repeated twice. Consequently, 96 and 72 tests were conducted for straight flanging and rotary bending, respectively.

Table 1
Chemical compositions of the materials

Material	***% Fe***	***% C***	***% Si***	**%M*n***	***% Cr***	***% Ni***	***% Cu***	***% Ti***	***% Al***	***% V***	***% W***
DC01 #1	99.5	0.032	0.021	0.18	0.022	0.011	0.025	0.002	0.051	0.004	0.04
DC01 #2	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	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	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	82.7	0.049	0.246	0.247	16.2	0.138	0.213	0.005	0.006	0.09	0.02

Table 2
Mechanical properties of DC01 and SAE 430 samples used in the experiments

Material Name	Yield Strength [MPa]	Tensile Strength [MPa]	Tensile Elongation [%]	Elongation at Break [%]	Strain Hardening Exponent	Strength Coefficient [MPa]
DC01 #1-RD	246	342	19	27	0.21	594
DC01 #1-TD	243	338	19	25	0.2	580
DC01 #2-RD	277	355	21	31	0.2	604
DC01 #2-TD	284	356	19	26	0.2	605
SAE 430 #1-RD	307	479	23	31	0.3	974
SAE 430 #1-TD	318	487	22	29	0.28	959
SAE 430 #2-RD	302	472	23	32	0.28	915
SAE 430 #2-TD	319	484	22	30	0.27	924
SAE 430 #3-RD	313	479	21	27	0.26	912
SAE 430 #3-TD	340	499	19	26	0.25	926

Table 3
Investigated parameters and their levels

	Parameter Levels		
Parameters	**1**	**2**	**3**
Method	Straight flanging	Rotary die bending	
Material	DC01 Drawing Quality Carbon Steel	SAE 430 Ferritic Stainless Steel	
Bending Radius	0.5 mm	2 mm	
Die Clearance	0.1 mm	0.2 mm	
Rolling Direction	Rolling Direction (RD)	Transverse Direction (TD)	
Flange Length	20 mm	30 mm	40 mm

Table 4
DOE Matrix of all experimental groups

	Method	Material	Parameters of Experiments			
			Bending Radius	**Die Clearance**	**Flange length**	**Bending Direction Parallel to**
1–3	Straight Flanging	SAE 430 #1 DC01 #1 SAE 430 #2	0.5	0.1	20	RD
			2	0.2	40	
4		DC01 #2	0.5	0.1	20	RD
					30	
			2	0.2	40	TD
5		SAE 430 #3	0.5	0.1	20	RD
					30	
			2	0.2	40	TD
6–8	Rotary Die Bending	SAE 430 #1 DC01-#1 SAE 430 #2	2	0.1	20	RD
				0.2	40	
9		DC01 #2	2	0.1	20	RD
					30	
				0.2	40	TD
10		SAE 430 #3	2	0.1	20	RD
					30	
				0.2	40	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 was conducted in the experimental setup shown in Fig. 4. Nitrogen cylinders were used again to apply the blank-holder force. After the sheet is compressed by the blank-holder, the rocker die moved vertically and applied 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.

After the experiments were conducted, the angle after unloading was measured using a 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 than the measuring system variability. When the results were statistically analyzed, the p-value was found smaller than 0.05. Hence it was concluded that variation of the measured values is statistically significant.

3. Results And Discussions

3.1 Straight flanging

The main effect plots of straight flanging are shown in Fig. 6 for the SAE 430 #1 (Sy 307 MPa) and #2 (Sy 302 MPa). It is observed that the amount of springback increases with increasing bending radius and die clearance for both variants. Contribution ratios of the factors and p-values were given in Table 5. Accordingly, the effect of the bending radius is in the first order, with values 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 are given in Fig. 7 for each variant. When the results of SAE 430 #1 (Sy 307 MPa) are examined, for both die radii, flange length has no effect. When the die radius is 0.5 mm, the impact of the die clearance becomes unclear (± 1%). However, when the die radius is 2.0 mm, and the clearance is increased from 0.1 to 0.2 mm, an average increase of 2.4% is encountered in springback. For the die radius of 2.0 mm, the springback varies between 3.4% and 6.0%.

An interaction between die clearance and bending radius was observed for SAE 430 #2 (Sy 302 MPa). As the clearance increases, springback increases. This effect is more evident, especially in the larger die radius. When the die radius is 2.0 mm, and the die clearance is increased from 0.1 mm to 0.2 mm, an average increase of 2.7% is encountered in springback. While the die radius is 2.0 mm, the springback varies between 3.4% and 6.6%.

Table 5
Contribution ratios and P values of the factors on springback in straight flanging process

Factors	SAE 430 #1		SAE 430 #2	
	Contribution	P-Value	Contribution	P-Value
Bending Radius (mm)	69.09%	0.000	59.58%	0.000
Flange Length (mm)	0.67%	0.066	0.29%	0.277
Die Clearance (mm)	15.68%	0.000	18.01%	0.000
Bending Radius *Die Clearance (mm)	13.33%	0.000	19.72%	0.000
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%	

The experiments were conducted for SAE 430 #3 (Sy 313 MPa) at three flange lengths and two directions besides two levels of die radius and clearance. It is understood that only the die radius has a significant effect on springback in this material, as shown in Fig. 8. When the interaction graph was examined (Fig. 8), it was concluded that the amount of springback increases with increasing flange length, but does not differ significantly between the flange lengths of 30 and 40 mm for the smaller radius value. In the larger die radius, the amount of springback is higher. With the increase of the flange length, the amount of springback decreases and then increases. On the other hand, the rolling direction does not have a significant effect on springback. Although the yield strength varies depending on the rolling direction, when the grain distribution of the materials is examined, as can be seen in Fig. 9, it can be said that it displays a homogeneous distribution in parallel and transverse rolling directions. When the die radius is 2.0 mm, the amount of springback varies between 3.0% and 3.8%. This result showed that SAE 430 #3 was affected by process conditions less than the other two SAE 430 variants.

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 only 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 4.0–6.9% for DC01 #2 (Sy 277 MPa). On the other hand, the rolling direction did not show a direct effect on springback 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 (bending) radius for all tested materials. The effect of springback is higher, at the large die radius (2.0 mm). In this radius value, the effects of changes caused by other parameters on the springback are more pronounced than that with the small die radius (0.5 mm). With the increase of the bending radius, the amount of plastic deformation encountered in the bending zone decreases. This decrease in plastic deformation causes more recovery in the material after the load applied during forming is removed. This explains the increase in springback as the radius increases.

When the material-borne interactions are examined, it is observed that the yield strength does not have a significant effect in the tested range (Fig. 11). So much so that when switching from the carbon steel group with yield strengths of 246 and 277 MPa to the stainless steel group with yield strengths of 307 and 302 MPa, there is no significant change in the amount of springback (± 1%). Here, it can be concluded that material parameters other than the yield strength may be valid.

3.2. Rotary die bending

In the rotary die bending process, it was found that changing clearance and flange length was not statistically meaningful for SAE 430 #1 (Sy 307 MPa) as the p-values were not less than 0.05 (Table 6). The clearance was found to be statistically significant for SAE 430 #2 (Sy 302 MPa) and #3 (Sy 313 MPa) with p-values of 0.02 and 0, respectively. The main effect plots of the parameters are given in Fig. 12. Also, 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. 13. 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 must be 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.

Table 6
ANOVA Table for SAE 430 #1

Factor	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Die Clearance (mm)	1	0.08034	23.81%	0.08034	0.080340	2.02	0.215
Flange length (mm)	1	0.05809	17.22%	0.05809	0.058089	1.46	0.281
Error	5	0.19894	58.97%	0.19894	0.039787		
Lack-of-Fit	1	0.17255	51.15%	0.17255	0.172549	26.16	0.007
Pure Error	4	0.02639	7.82%	0.02639	0.006597		
Total	7	0.33737	100.00%				

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 amounts range was given in Table 7. A comparison of processes and materials in terms of measured angles is given in Fig. 14. The effect of an increase in the die clearance is more pronounced for the straight bending 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.

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.

Table 7
The increase in springback and its ranges as a function of clearance (die radius 2 mm).

Material	Increase in springback		Springback range	
	Straight Flanging	Rotary Die Bending	Straight Flanging	Rotary Die Bending
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	unclear	0.3%	3.0% – 3.8%	3.1% – 3.7%
DC01 #1	2.8%	0.4%	3.7% – 7.3%	3.1% – 3.7%
DC01 #2	unclear	0.7%	4.0% – 6.9%	2.7% – 3.5%

The comparison of angle measurements for both processes at a die clearance of 0.2 mm is given in Fig. 15. As can be seen from the plot, the rotary die bending process produced consistently smaller springback angles except for the material of SAE 430 - #3. Average springback values and their variance for each process are shown in Fig. 16. The average variation in straight flanging was 1.23° and it is 0.11° in rotary die bending. As 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 springback angle, and thus it is a more robust process in the manufacturing of box-type parts and panels and other industrial applications.

When the material (steel type and yield strength) effects are evaluated, it is seen that the springback behaviors of different material groups show differences in the tested range (Fig. 17). 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.

4. Concluding Remarks

In this article, the effects of straight flanging and rotary die bending on springback are investigated using the design of experiments method and ANOVA. In the tests, EN DC01 carbon steel and SAE 430 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; bending 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:

- The average springback in rotary die bending as compared to straight flanging is 40% less for DC01, and 13% less for SAE 430.

- The range springback angle encountered in rotary die bending laid in a relatively narrower (0.6%) than that of straight flanging (2.6%).
- Steel sheets from different suppliers or in various parties from the same supplier may exhibit significantly different springback behavior under the same process conditions; however, rotary die bending covers that problem effectively.
- 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.

It can be concluded that rotary die bending yields a more stable springback behavior than straight flanging in the tested working range. Therefore, the rotary die bending method is more appropriate in the mass production of box-type parts and to keep the geometric deviations to the lowest level.

Declarations

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Figures

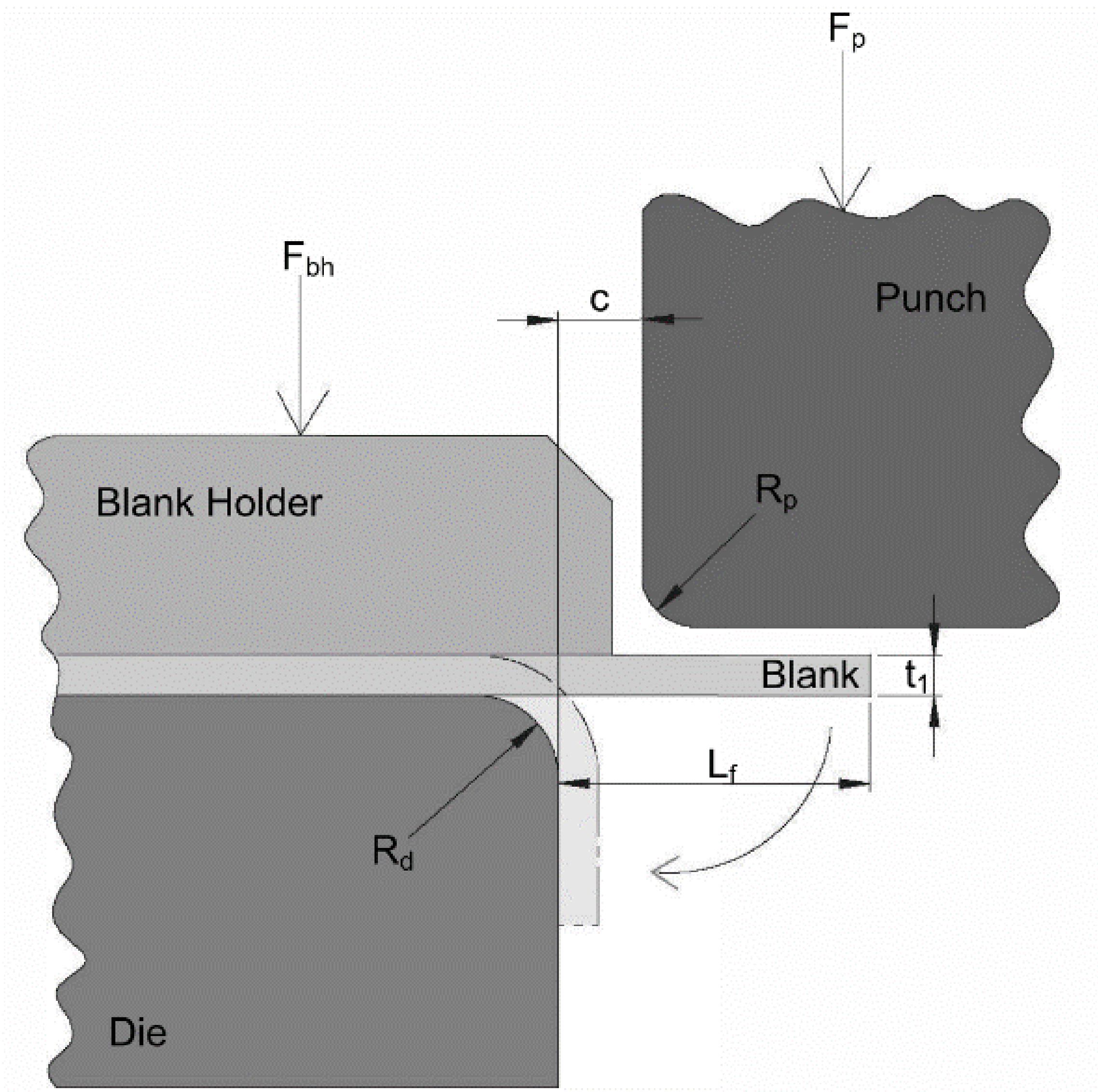

Figure 1

Straight flanging process

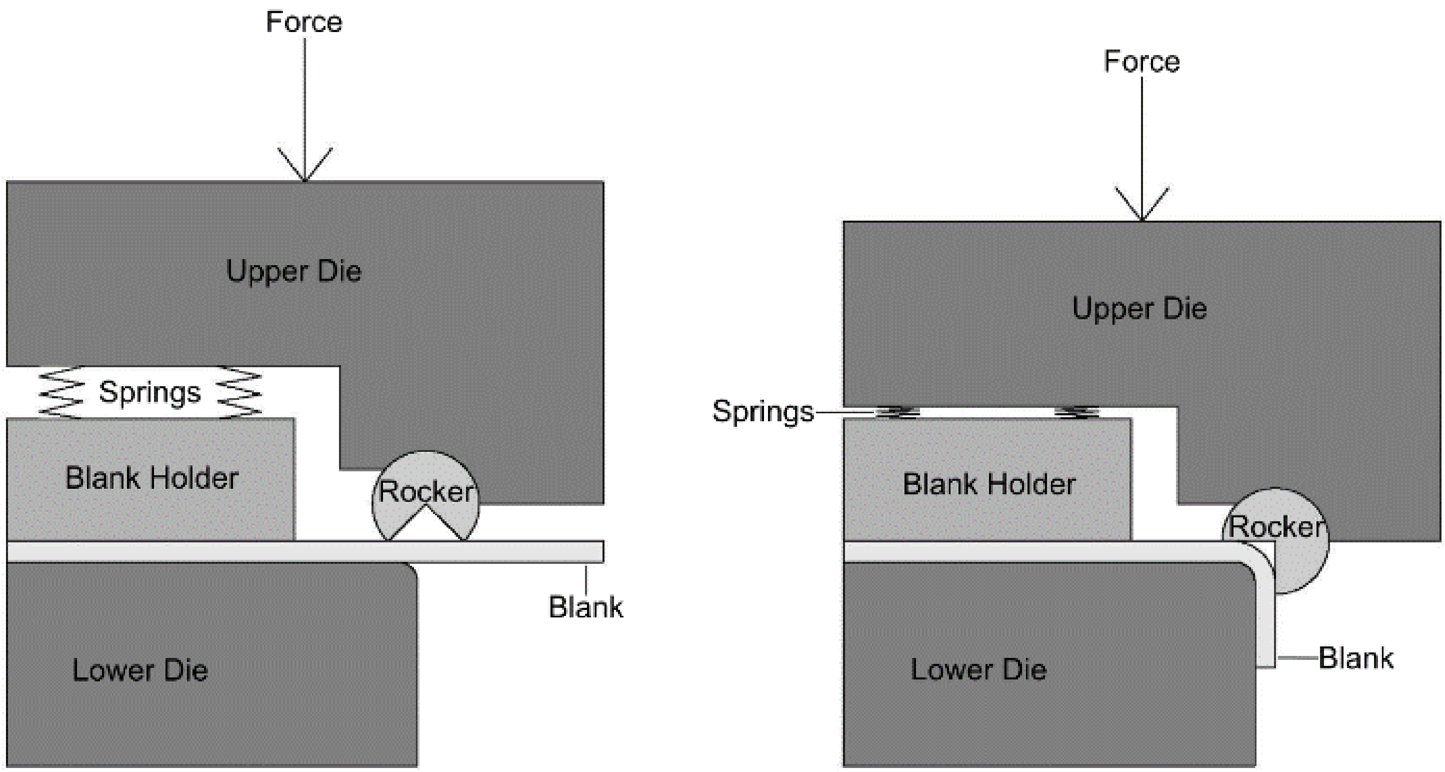

Figure 2

Rotary die bending process and its tools

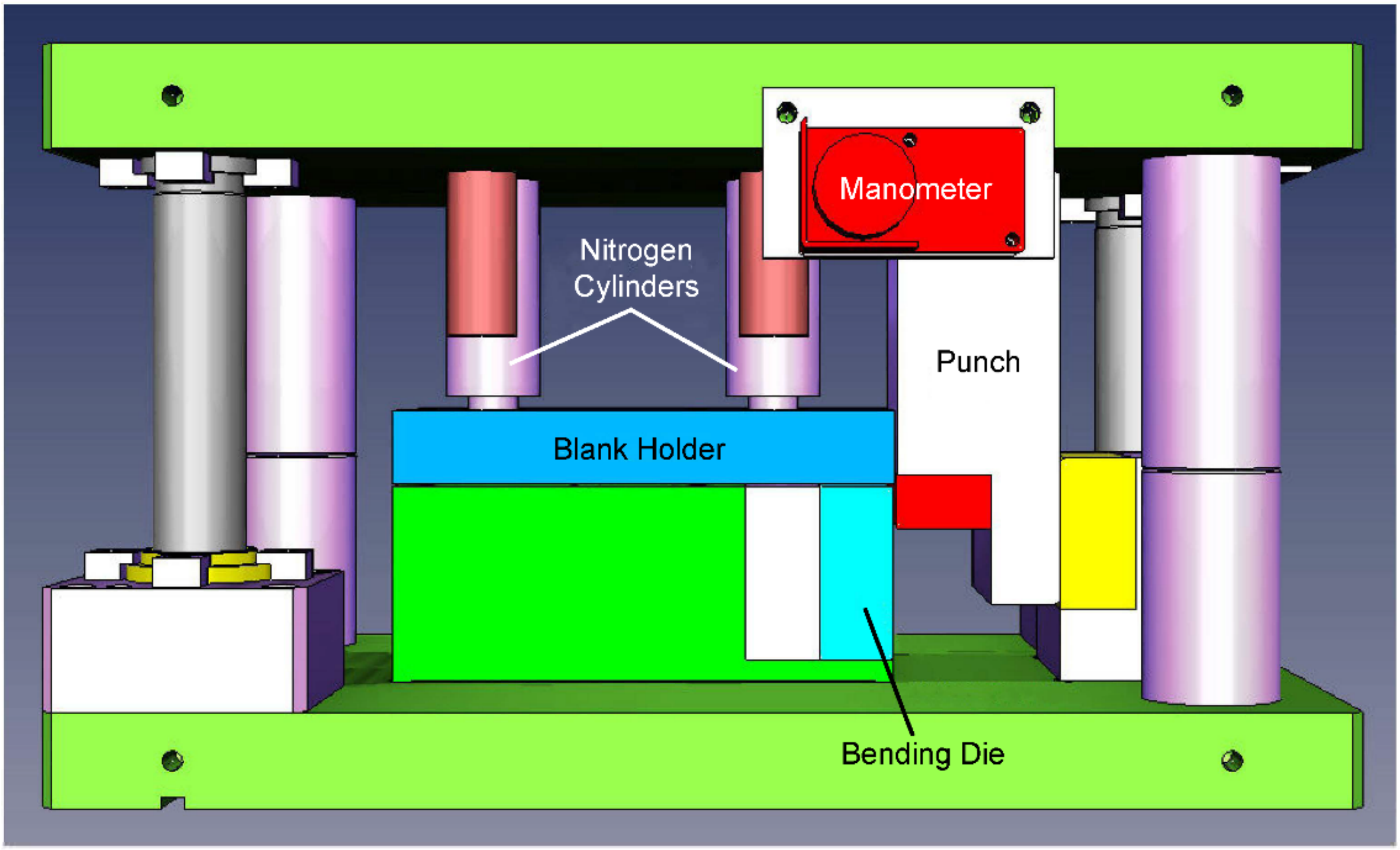

Figure 3

Straight flanging test setup

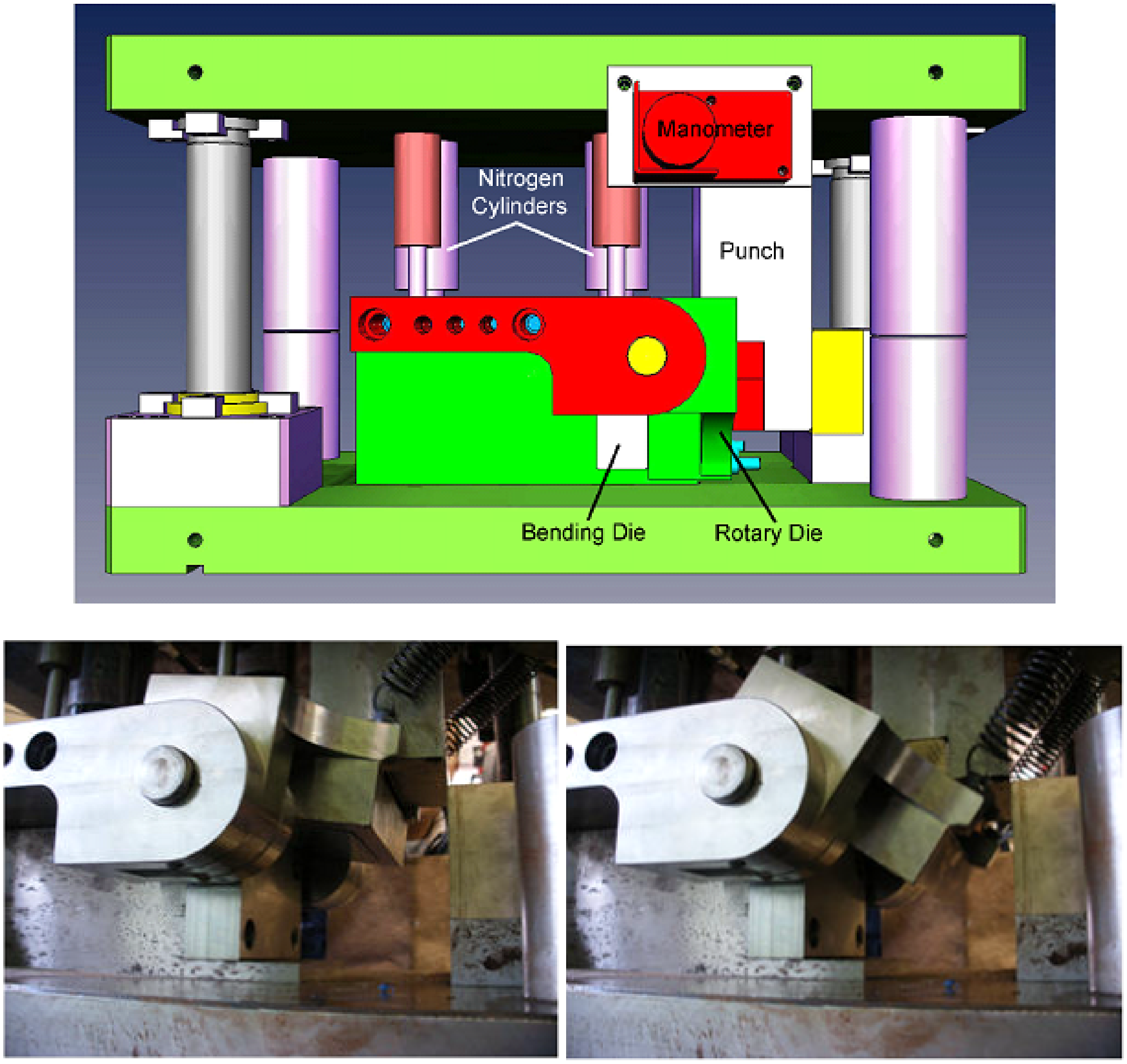

Figure 4

Rotary die bending test setup

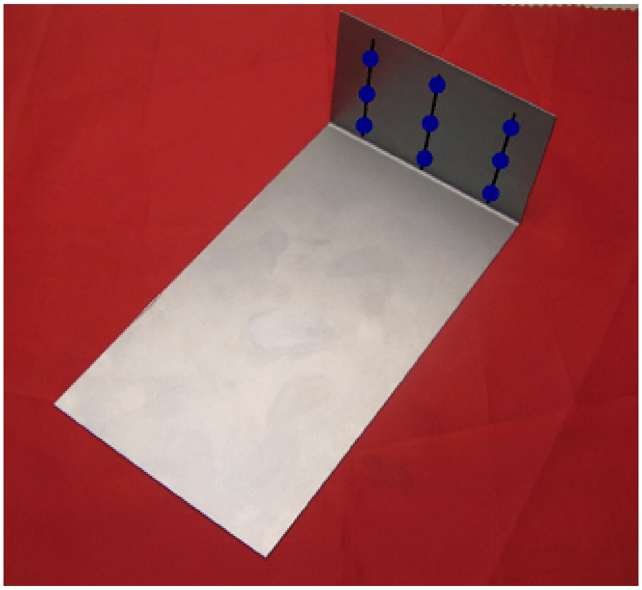

Figure 5

Measured points on a specimen

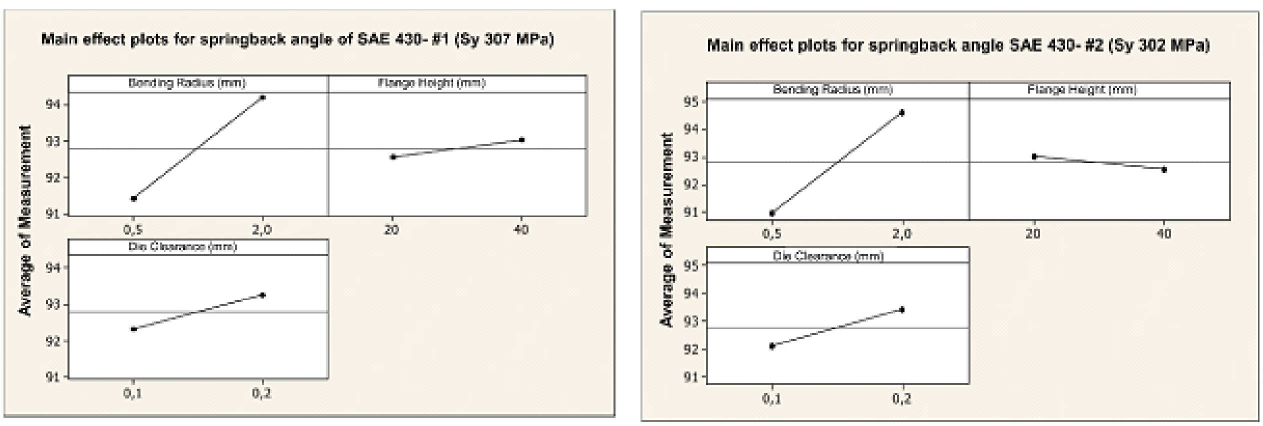

Figure 6

Main effect plots for straight flanging of SAE 430 #1 and #2

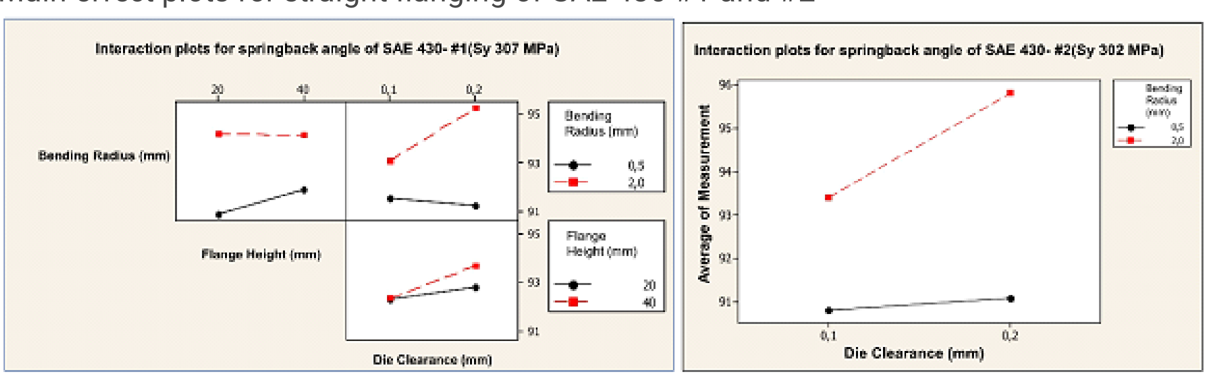

Figure 7

Interaction plots for straight flanging of SAE 430 #1 and #2

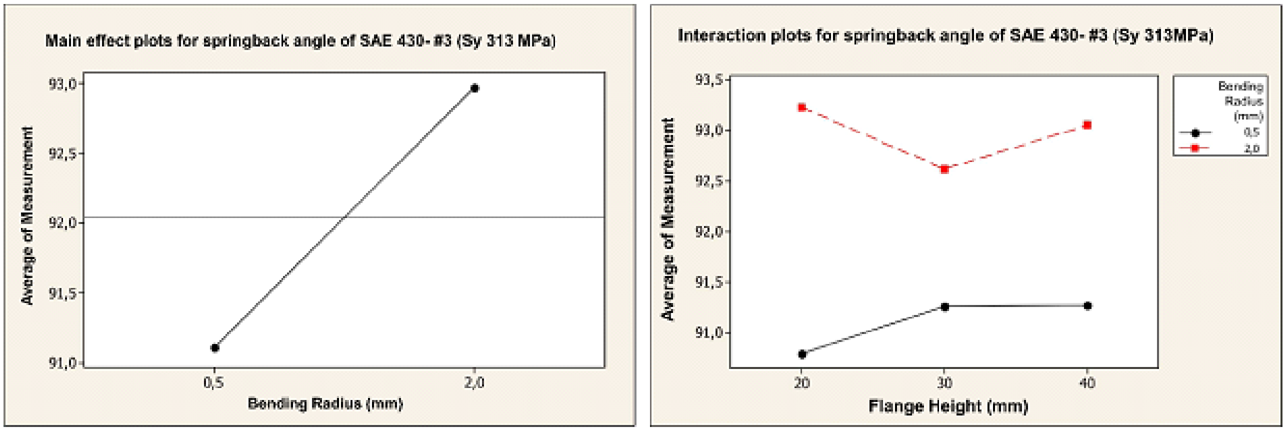

Figure 8

Main effect and interaction plots for straight flanging of SAE 430 #3

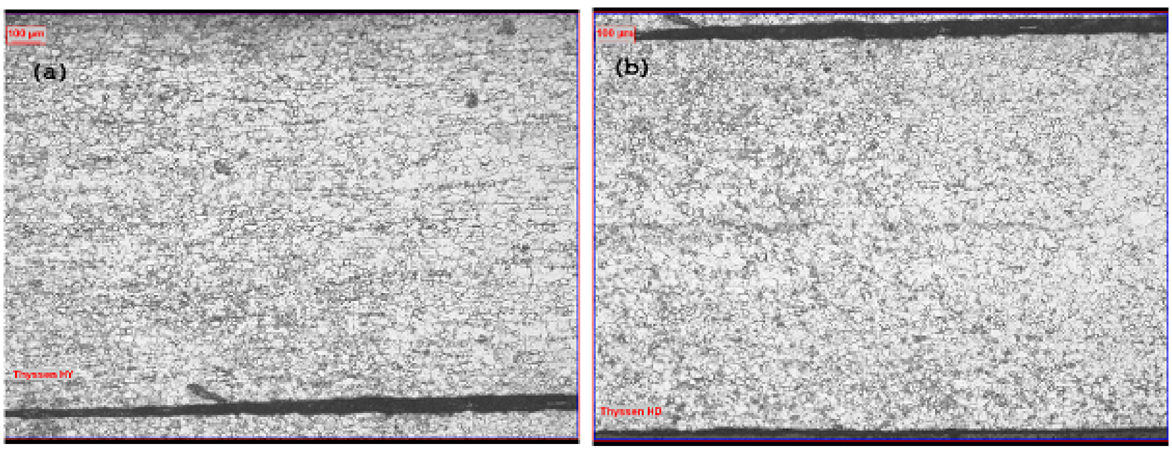

Figure 9

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

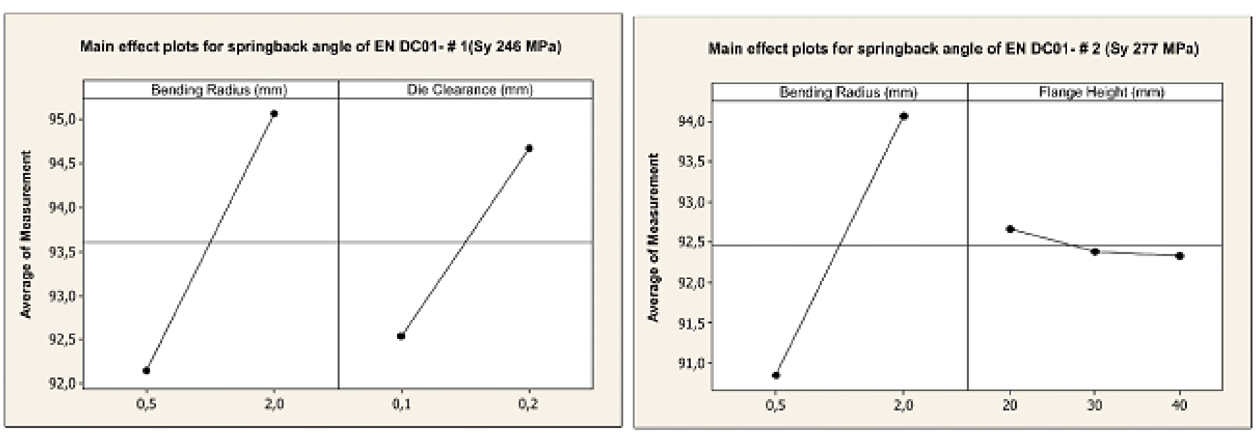

Figure 10

Main effect plots for straight flanging of DC01 #1 and #2

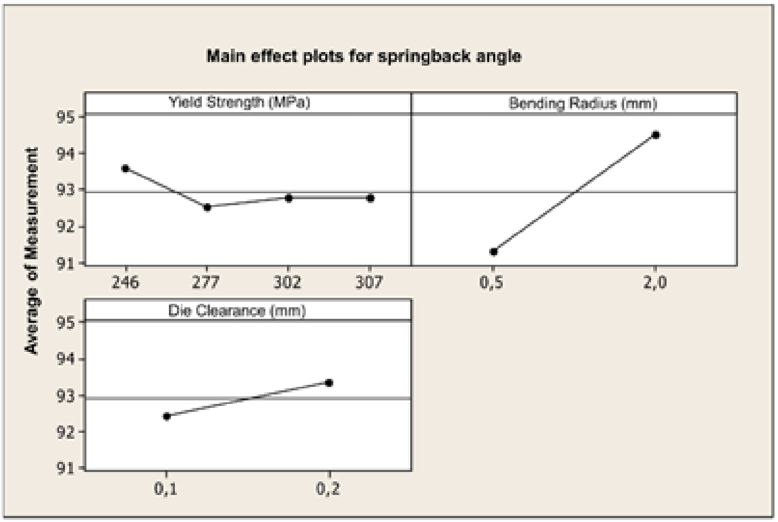

Figure 11

Main effect plots for rotary die bending (including all materials)

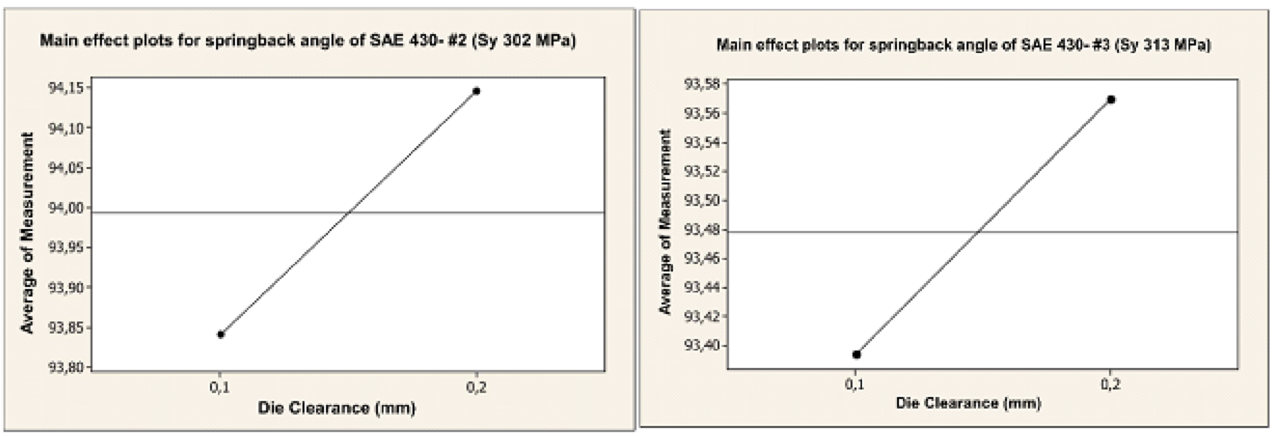

Figure 12

Main effect plots for rotary die bending of SAE 430 #2 and #3

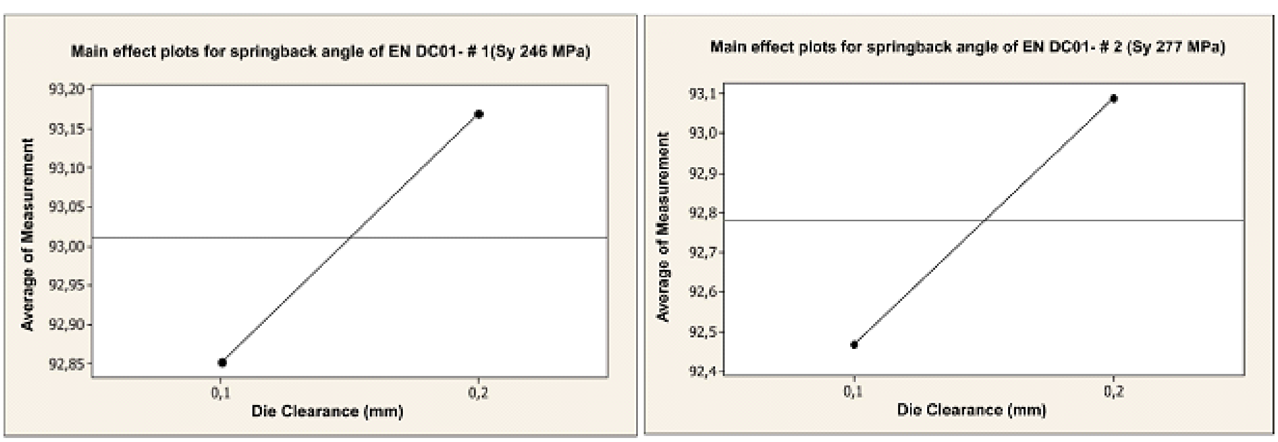

Figure 13

Main effect plots for rotary die bending of DC01 #1 and #2

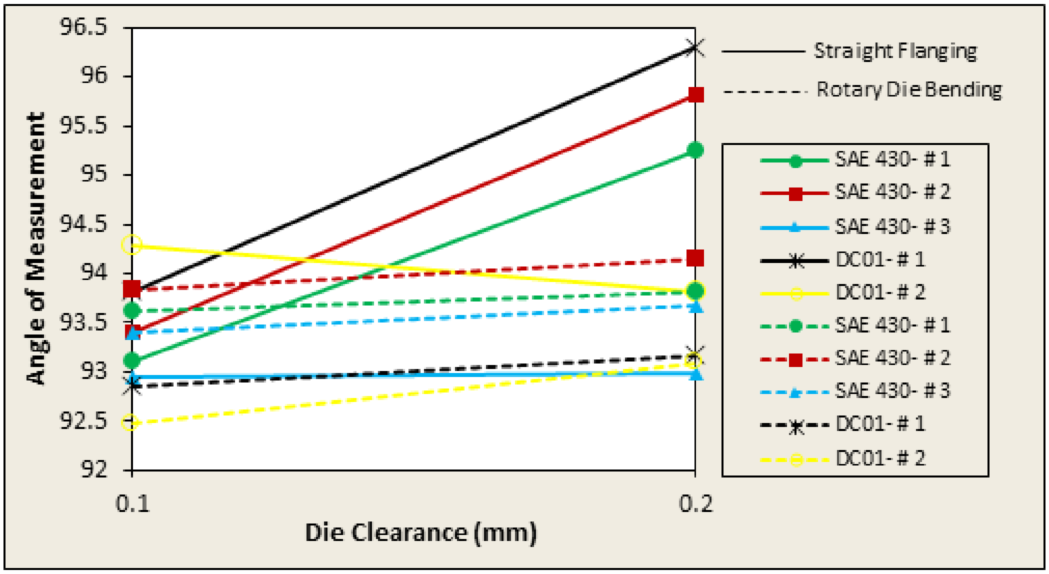

Figure 14

Comparison of average springback for all materials versus clearance (Rd=2 mm)

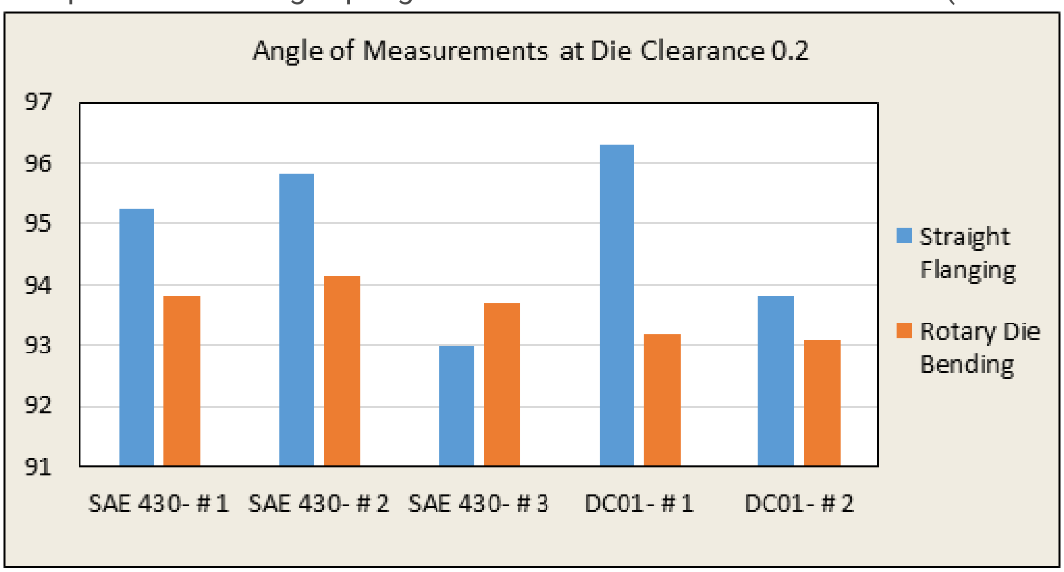

Figure 15

Comparison of both processes for all tested materials at 2 mm die radius and 0.2 mm die clearance

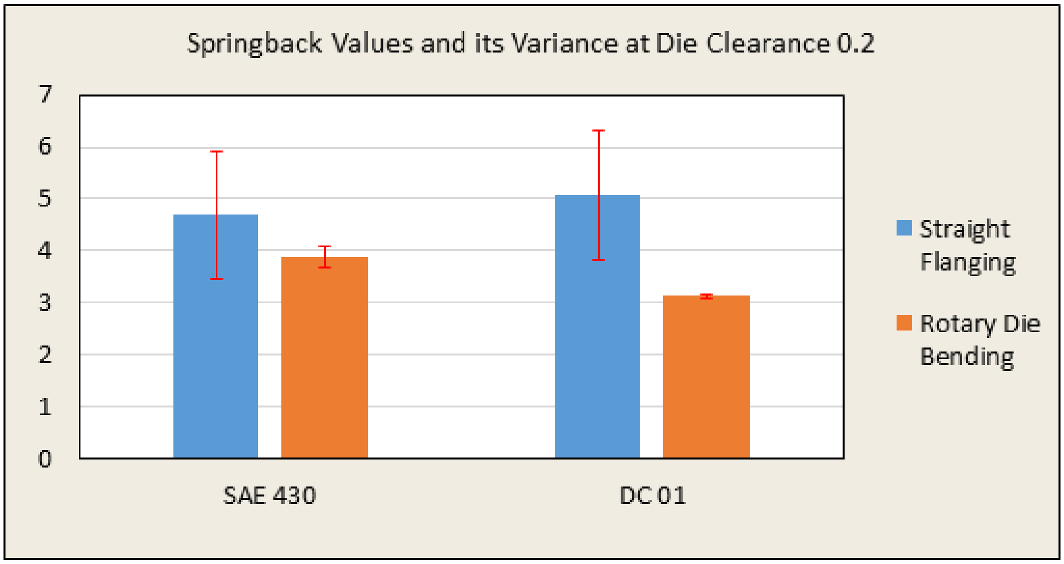

Figure 16

Average springback values and its variations at 2 mm die radius and 0.2 mm die clearance

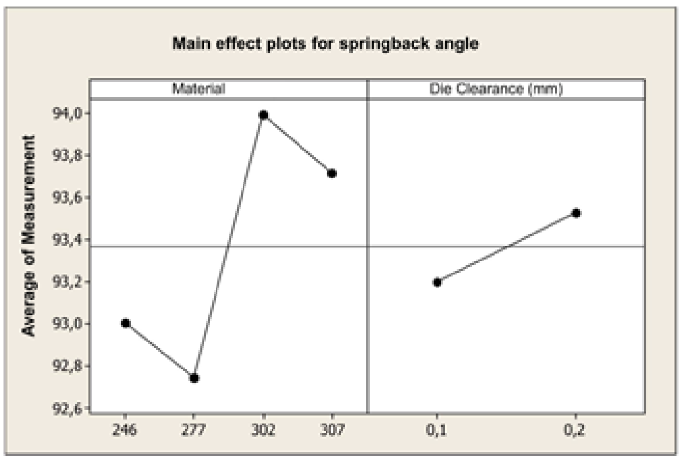

Figure 17

Material (yield strength) and die clearance based mean effect plots for rotary die bending