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STATISTICAL ANALYSIS OF THE V-TOOL BENDING PROCESS PARAMETERS IN THE BENDING OF HC260Y STEEL

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This paper presents statistical analysis of the parameters in the V-tool bending process of the HC260Y steel. Assessment of the mathematical model and analysis of variance (ANOVA) were performed within the design of experiments. The hydraulic testing machine Amsler and the developed V-tool were used in the experiments.

Key words: HC260Y, bending, mathematical model, process parameters, design of experiments

INTRODUCTION

The V-tool bending refers to a process often performed in the sheet metal industry. High strength steels bear relatively high amounts of yield stress $R_{p0,2}$, which results in high amounts of elastic springback after bending. From the Hooke's law, stress is $\sigma = E \cdot \varepsilon$, so when the inner stresses in the bent sheet section go to the equilibrium state, the larger amount of springback is observed for high strength steels [1]. The bending angle before tool unloading is denoted with α_1, and the bending angle after tool unloading (and springback) is α_2 as shown in Figure 1. The difference between two sheet metal angles is defined as the bending error [2]:

$$O_a = \frac{\alpha_2 - \alpha_1}{\alpha_1} \tag{1}$$

In the process of V-tool bending, the variables that influence the amount of springback are [1,3,4]:

- punch radius r_i
- die shoulder width w
- sheet metal thickness s
- friction factor μ
- radii of lower V-tool r_n
- calibration force F_{cal}
- material strain hardening function
- material anisotropy
- strain rate $\dot{\varphi}$

Some of the abovementioned variables are process parameters (they can be changed in the V-bending process presented in Figure 2), while other variables are material-related.

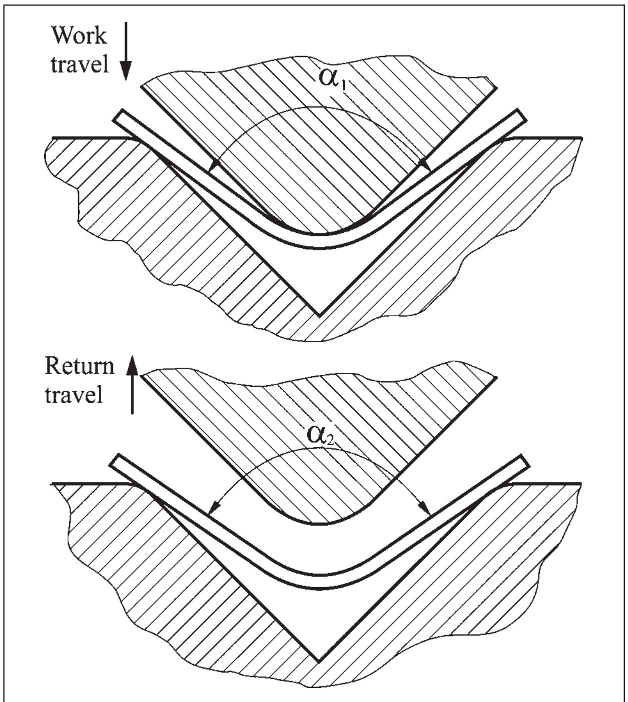

Figure 1 Bending angles before and after tool unloading

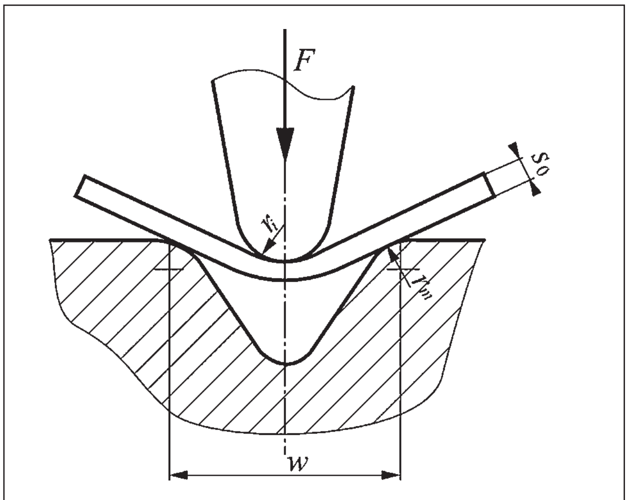

Figure 2 Bending process parameters [5]

EXPERIMENTAL WORK

The three process parameters were selected, and they were set at two different levels for the experiments – 2^3. The punch radius was set as r_i = 3 mm, and r_i = 8 mm, as

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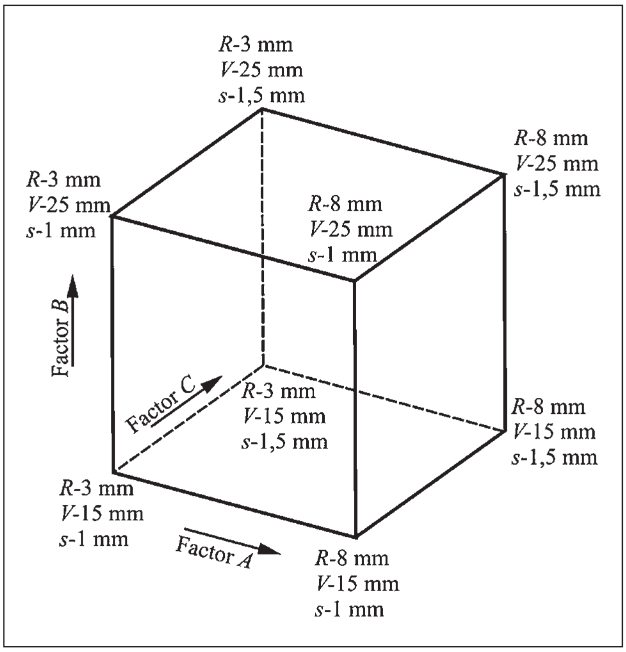

Figure 3 Design of experiments

it is often used in the sheet metal production. The die width was set as w = 15 mm, and w = 25 mm (dictated by available space on the tool). Sheet thickness was used as s = 1 mm, and s = 1,5 mm, as presented in Figure 3.

The angle α_1 was measured digitally (from image). The angle α_2 was measured digitally after unloading, with a high precision protractor. The results (Table 1) were used for the statistical analysis.

RESULTS AND DISCUSSION

The data obtained in the experiments Table 1 were processed in the Design Expert software.

Table 1 **Experiment results**

No:	Factor A r_1 / mm	Factor B w / mm	Factor C s / mm	Angle α_2 / °
7	8	25	1	95,2
5	3	25	1	89,6
1	3	15	1	92,3
16	8	25	1,5	92,4
11	8	15	1,5	106,7
3	8	15	1	101,8
12	8	15	1,5	102,9
6	3	25	1	89,2
8	8	25	1	94,8
4	8	15	1	98,5
13	3	25	1,5	89,6
10	3	15	1,5	94,1
15	8	25	1,5	92,3
9	3	15	1,5	91,4
14	3	25	1,5	88,8
2	3	15	1	91,8

In the Figure 4, there is half-normal plot presented with the significant factors visible on the right side (marked ones). The line on the left side refers to the non-significant factors for the resulting angle α_2 / °.

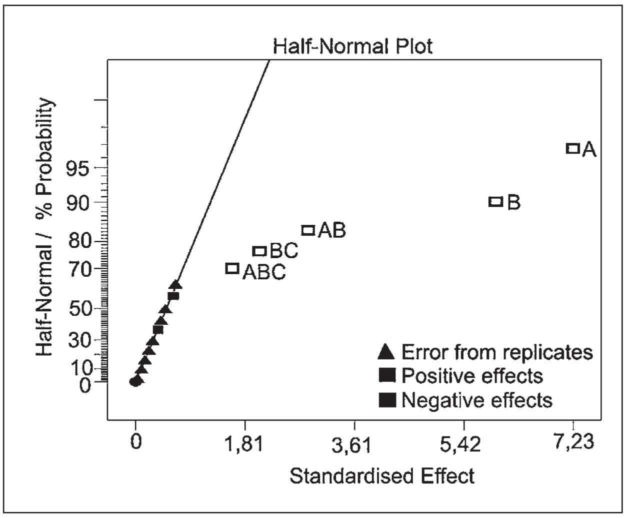

Figure 4 Half-normal plot

The significance of factors (and their interactions) is calculated from the positive or negative effects on the result (α_2 / °):

$$Ef(y) = \frac{\sum Y_+}{n_+} - \frac{\sum Y_-}{n_-} \quad (2)$$

Where Y is the effect, n is the number of factors on lower (-) or upper level (+) [6-8].

For the factorial design of experiments, the sum of squares can be determined [6-8]:

$$SS = \frac{N}{4}\left(Ef^2\right) \quad (3)$$

where N is the total number of experiments.

For the selected factors (Figure 4), the Sum of Squares for the model is calculated as [6-8]:

$$SS_{\text{model}} = SS_A + SS_B + SS_{AB} + SS_{BC} + SS_{ABC} \quad (4)$$

Figure 5 shows significant factors through the Pareto analysis, which confirms choices from Figure 4. Factors are arranged in the order of significance (magnitude of effects on α_2 / °).

Table 2 contains data resulting from the calculation of variance (ANOVA). Data are shown for the selected factors (and their interactions) in Figures 4 and 5. DOF stands for Degrees Of Freedom. For each selected factor (A, B, AB, etc.), effects are calculated with the expression (2) from upper (+) and lower (-) level, meaning that each effect has one degree of freedom [6-8]. For the seven selected factors (Table 2), the seven degrees of freedom are used for the mathematical model.

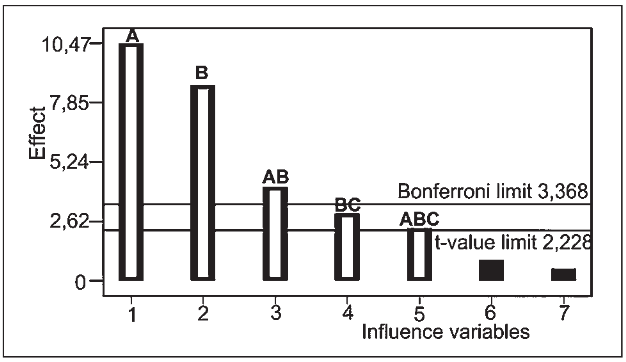

Figure 5 Pareto analysis of significant factors

Table 2 **ANOVA**

ANOVA					
Source	Sum of Squares(*SS*)	DOF (*df*)	MeanSquare (*MS*)	*F* - value	*p*- value Prob>*F*
Model	412,08	7	58,868	27,834	< 0,0001
Factor A; r_i	208,8	1	208,80	98,725	< 0,0001
Factor B; *w*	141,61	1	141,61	66,955	< 0,0001
Factor C; *s*	1,563	1	1,563	0,7388	0,4151
AB	32,49	1	32,49	15,362	0,0044
AC	0,563	1	0,563	0,2659	0,6200
BC	16,81	1	16,81	7,9479	0,0225
ABC	10,24	1	10,24	4,8416	0,0590
Resid.	16,92	8	2,115		
Cor. Total	428,99	15			

Mean square is calculated by the expression [6-8]:

$$MS = \frac{SS}{df} \tag{4}$$

The *F*-factor is furthermore calculated as:

$$F_{\text{model}} = \frac{MS_{\text{model}}}{MS_{\text{resid}}}; \quad F_A = \frac{MS_{\text{A}}}{MS_{\text{resid}}}; \quad F_B = \frac{MS_{\text{B}}}{MS_{\text{resid}}}; \quad F_{AB} = \frac{MS_{\text{AB}}}{MS_{\text{resid}}} \tag{5}$$

It can be seen in the Table 2 that both punch radius r_i and the V-tool width *w* have high *F* value, so it can be stated with 99,9 % probability that these process parameters were significant for the α_2 / ° angle. Furthermore, it can be stated that the interaction of factors *AB* was significant with 99 % probability.

The obtained mathematical model is:

$$\alpha_2 = 101,075 - 3,5 \cdot r_i - 0,703 \cdot w - 12,16 \cdot s + 0,206 \cdot r_i \cdot w + 5,42 \cdot r_i \cdot s + 0,588 \cdot w \cdot s - 0,256 \cdot r_i \cdot w \cdot s \tag{6}$$

The coefficient of determination for the obtained mathematical model is R^2 = 0,9606 and the modified coefficient of determination $\bar{R}^2$ = 0,926.

The factors (and interactions) from equation (6), which are proven non-significant, are left in the equation for calculation purposes and mathematical model integrity.

Figure 6 presents respond surface (angle α_2 as a function of punch radius r_i and V-tool width *w*) for the sheet thickness of *s* = 1 mm.

Figure 7 shows the response surface for the sheet thickness of *s* = 1,5 mm.

CONCLUSION

In this paper, the V-tool bending process parameters were tested according to the factorial design of experiment. The tested material was interstitial free (IF) automobile grade steel HC260Y. The goal of this study was to identify significant parameters and their influence on the sheet metal unloading angle α_2. This angle was measured digitally (digital image), and with the high precision digital protractor. The results obtained within experiments were statistically processed. It was determined that tool punch radius and V-tool die width were significant factors.

Sheet metal thickness was not significant factor, although it had some minor influence on the angle α_2. The mathematical model (6) was derived from the experiments.

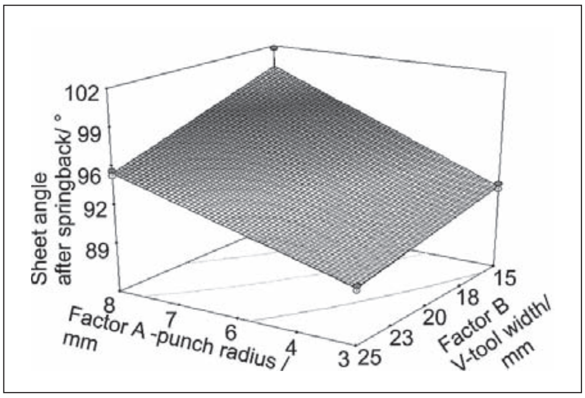

Figure 6 Response surface for the sheet thickness of s = 1 mm

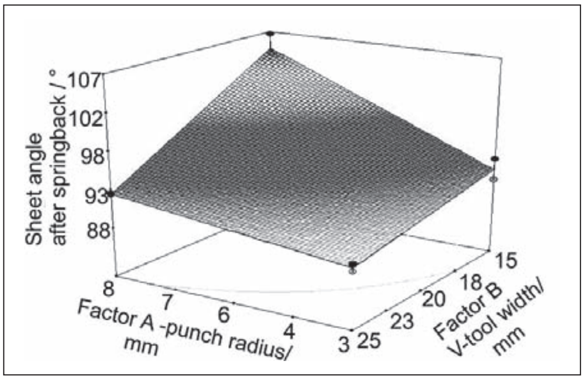

Figure 7 Response surface for the sheet thickness of *s* = 1,5 mm

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Note: Responsible person for English translation is prof. Martina Šuto (J.J. Strossmayer University of Osijek) and prof. Marina Karšić