Analysis of height dimensions of relatively high box-parts in their drawing from variable thickness blanks by full factorial experiment implementation

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Abstract. This article is devoted to an experimental study of the error in the contour height of relatively high box-parts with large radiuses of angular curves manufactured by drawing operation from a tailor welded blanks with variable thickness made of high-strength steel. The advantages of usage of tailor welded blanks with variable thickness are a reduction in the cost of the blanks by reducing material consumption compared to the “classic” uniform blanks, the ability to create a design of the stamped part in accordance with the requirements for operational properties, and a reduction in the mass of the stamped part as a whole.

1. Introduction

Currently the implementation of some new progressive types of metal sheet blanks (for example tailored welded sheet blanks (TWB) of variable thickness) in the development of the ways to intensify the sheet stamping process during the production of the detail parts and components for a number of sectors of industry and other branches of the economy is constantly increasing. For example in order to reduce the weight and the cost of the parts and also to manage the strength characteristics of the car [1] to improve its passive safety the modern automotive industry actively develops a new direction of the TWB with variable thickness [2, 3, 4]. At the moment due to the constantly changes of the body design, casings, aprons, tanks and other items produced during the "drawing" process the need to use TWB of variable thickness increases as well as in the other sectors of the national economy including the aerospace industry [5, 6].

2. Materials and Methods

The accuracy is a complex indicator which gives an idea about the perfection of the technological process and shows the specific features of one or other stamping process in general and sheet metal stamping in particular. For example the accuracy assessment of the sheet-blank stamping method of "drawing" is based on the study of errors of the initial blanks, the inaccuracy of the technological process, the features of force conditions and the mode of deformation.

The factors influencing the inaccuracy with regard to the height of the box-parts during the drawing process can be classified according to the nature of their manifestation:

1. The factors determine some occasional errors which mainly affect the value of the instantaneous scattering field of a random variable of the box’s height dimension as follows:
   a) errors of the geometric characteristics of the initial blanks;
   b) fluctuation of some physical and mechanical properties of the initial blanks’ material because of the variability of the chemical composition and because of the heterogeneity of the raw material structure of the blanks;
   c) errors arising from the changes of the friction conditions in the die cavity and assessed through the changes in the value of the contact friction coefficient;
d) errors arising from the incorrect placing of the initial blank in the die;

2. The factors defining some systematic constant errors/inaccuracies in the production of the kit of parts comprise the geometric error of the real dimensions of the die tooling, including the inhomogeneity of the roughness of the die surfaces involved in the formation process and the anisotropy of mechanical properties as well [7]. In some cases, for example, during the automatic stamping the geometric dimensions of the die forming surfaces and the friction conditions can change due to the action of the temperature factor. If so, the mentioned factors determine the errors which can act within a certain period as systematic and naturally changing ones.

Figure 1. The sketch of the final box-part after "drawing" operation

Figure 1 shows a sketch of the final box-part and the geometric parameters of which are shown in Table 1. The initial sheet material for the experiments is high-strength steel HX260PD from a rage of RS-steels which presents a high-strength and rolled product made of rephosphorized steel. The shape formation of the initial sheet blanks was performed according to the well-known method [8] for relatively high boxes with relatively large radiuses of angular rounding.

Composite blanks were used for making experiments which parts were butt-welded by laser; the quality control of welding was carried out according to the standard [9]. The experiments [10] were performed in the laboratory of the Department MK1 "Machine-Building technologies" of Kaluga branch of Bauman Moscow State Technical University (MSTU named after N.E. Bauman). The drawing of box-parts was implemented in an experimental die without using of any additional force to the surface of the initial sheet blank by "upper" and "lower" blank holder and without any lubrication. Two types of initial TWB (1-st type of blanks: $S_1=1.9$ mm; $S_2=2.4$ mm; thickness difference $\Delta S=0.5$ mm; 2-nd type of blanks: $S_1=1.4$ mm; $S_2=2.4$ mm; thickness difference $\Delta S=1.0$ mm) and 8 sizes were used three times for all experiments while changing the calculated (rated) height $H$ of the box-part from 23.15 mm up to 30.15 mm. The welded seam was at the center of the sheet blank, see Figure 1. The results of all experiments are presented at pictures Figure 2 and Figure 3.
Table 1. Geometric parameters of the final box part after the "drawing" operation

| №  | Geometric parameters of the box-part                                                                 |
|----|-----------------------------------------------------------------------------------------------------|
| 1  | thickness of material:                                                                             |
|    | 1-st type of blanks - $S_1 = 1.9\, mm$; $S_2 = 2.4\, mm$; thickness difference $\Delta S = 0.5\, mm$; |
|    | 2-nd type of blanks: $S_1 = 1.4\, mm$; $S_2 = 2.4\, mm$; thickness difference $\Delta S = 1.0\, mm$; |
| 2  | calculated (rated) height of the box-part: $H$, mm                                               |
| 3  | radius of corner curvature: $R_y = 10\, mm$                                                      |
| 4  | radius of bottom curvature: $R_d = 10\, mm$                                                      |
| 5  | minimum deviation (error) of the calculated (rated) height of the box with regard to the part of   |
|    | the contour of thinner material: $\Delta H_{1\text{min}}$, mm                                    |
| 6  | maximum deviation (error) of the calculated (rated) height of the box with regard to the part of   |
|    | the contour of thinner material: $\Delta H_{1\text{max}}$, mm                                    |
| 7  | minimum deviation (error) of the calculated (rated) box height with regard to the part of the     |
|    | contour of thicker material: $\Delta H_{2\text{min}}$, mm                                        |
| 8  | maximum deviation (error) of the calculated (rated) height of the box with regard to the part of   |
|    | the contour of thicker material: $\Delta H_{2\text{max}}$, mm                                    |
| 9  | the width of the box-part: $A = 40\, mm$                                                         |
| 10 | the length of the box-part: $B = 80\, mm$                                                        |

The arithmetic mean $\Delta H_i$ is calculated by:

$$\Delta H_i = \frac{(H_{i\text{min}} + H_{i\text{max}})}{2} \quad (1)$$

Figure 2. Experimental curves reg. the dependence of errors $\Delta H$ in the height of the box-part contour ($S_1=1.9\, mm$, $S_2=2.4\, mm$, $\Delta S=0.5\, mm$) on the deformation degree $m$

Figure 3. Experimental curves reg. the dependence of errors $\Delta H$ in the height of the box-part contour ($S_1=1.4\, mm$, $S_2=2.4\, mm$, $\Delta S=1.0\, mm$) on the deformation degree $m$
3. Results and discussions
The full factorial experiment $2^3$ matrix, its results and also the levels of factors at the natural and normalized scales are presented in Table 2 and respectively in Table 3 where $\Delta S$ (thickness difference) and $m$ (deformation degree) are the investigated factors at the coded scale; $\bar{\Delta H}$ is the average value of the errors/inaccuracies reg. the height in every $i$-th experiment; $S_i^2$ is the dispersion in $i$-th experiment.

| Factors | Factors level | Interval |
|---------|--------------|----------|
| $m$     | +1           | 1.53     |
|         | 0            | 1.435    |
|         | -1           | 1.34     |
| $\Delta S, \text{mm}$ | 1.0 | 0.75 | 0.5 | 0.25 |

| Table 2. Factors level at natural and normalized scales. |
| Ne | $m$ | $\Delta S, \text{mm}$ | $\bar{\Delta H}, \text{mm}$ | $S_i^2$ |
|----|-----|-----------------------|-----------------------|-------|
| 1  | +   | +                     | 2.50                  | 2.50  | 0.0016 |
| 2  | -   | +                     | 0.89                  | 0.95  | 0.0036 |
| 3  | +   | -                     | 2.11                  | 2.19  | 2.15  | 0.0016 |
| 4  | -   | -                     | 0.85                  | 0.88  | 0.82  | 0.85  | 0.0009 |

To create a model (2) of regression analysis we used a generally accepted method [11], when an adequate regression model was obtained at the normalized scale of factor levels in the statistical processing of the results of full factorial experiment $2^3$:

$$y(\Delta H) = 1.61 + 0.71 \cdot m + 0.11 \cdot \Delta S + 0.06 \cdot m \cdot \Delta S$$ (2)

The value and the sign of the coefficients (plus—minus) in the regression equation indicate the strength and the character of influence of the investigated factors on the relative error/inaccuracy of the box-part’s height.

From the analysis of the regression model it follows that the deformation degree $m$ has the greatest influence on $\Delta H$ (the average value of the error reg. the height of box-part). The effect of the first one is almost 7 times more than the effect of thickness difference $\Delta S$.

The analysis of variance is used to select in a more objective way some factors which have the strongest impact on the response ($\Delta H$) and makes it possible to determine the contribution of factors and their interactions to the variance (variation) of the response ($\Delta H$). So the deformation degree $m$ has 96.84% and makes the greatest contribution of to the overall response variance, the thickness difference $\Delta S$ has 2.41% and the paired effect of the factors $m$ and $\Delta S$ is 0.75%.

4. Conclusions
The experimental results indicate the need to make certain corrections in the calculation of the optimum contour tailor welded blanks of variable thickness for drawing box-shaped parts as confirmed by well-known researches [12, 13] aiming at some recommendations for calculation of the contour of the initial tailor welded blanks to avoid cutting of the box-part’s contour after drawing process and to get a relatively smooth contour of the item where some inherent roughness or errors will be kept within tolerance on the height of the box-part.

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