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Experimental modeling of fluid pressure during hydroforming of welded plates

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A B S T R A C T

The procedure of hydroforming belongs to one of the modern methods of sheet and tube design, usually of complex configuration. Research in the field of plastic forming using fluids usually relates to the analysis of important parameters that would enable high-quality design of elements and execution of the process in stable conditions. The hydroforming process of welded sheets found its application in manufacturing of tanks and other sheet parts in automotive industry, where, in addition to technical and technological characteristics of the obtained piece, it is necessary to achieve stability of the process and its economic feasibility. Experimental research in this paper had been aimed at the analysis of results and modeling of working fluid pressure during hydroforming of welded sheets of two kinds of material (St 37 and Al 99.5) for two sheet thicknesses (1.5 mm and 2.0 mm). Modeling was done by regression method, whose analysis is the determination of functional relationships between a dependent variable and two independent variables. Application of mathematical modeling method enabled working fluid pressure which confirmed the impact of input variables of hydroforming process (yield strength and sheets thickness) onto the values of working fluid pressure. Experimental results obtained for working fluid pressure enabled easier planning and projection of hydroforming process.

A R T I C L E I N F O

Keywords:
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1. Introduction

The development of the automotive industry is based on the emergence of new materials and technologies for their processing. New methods of processing materials enable the achievement of technical and technological characteristics required by the market of the finished product.

Hydroforming is the process of forming sheets and tubes during which, by function of fluids under pressure, pieces, most often of complex shapes, are formed for the automotive industry [1-4].

The process is quick, inexpensive and meets the quality of shaped elements. So far, a number of studies have been conducted that included analytical, experimental, numerical, mathematical and other analyses of various treatment processes [5-10]. Hein and Vollertsen (1999) have conducted experimental and numerical research in order to establish the technological and economic characteristics of the process during hydroforming of double sheets [11]. The analysis and comparison of conventional deep drawing and process of sheet element hydroforming by using the finite element method [12] is the area of research of Chang et al. (2001). By application of CCD (Charge Coupled Device) camera, Groche, P. et al. (2007) conducted the control of sealing system during the execution of sheet hydroforming process.

The control of fluid pressure upon hydroforming of double sheets is an area of research of Assempour and Emami (2009) [13]. In their paper Ertugrul et al. (2009) analyzed hydroforming of laser welded sheets [14].

In addition, Liewald and Bolay (2010) in their paper state the analysis of hydroforming process of double sheets [15]. By application of finite element method (FEM) Zhang et al. (2015) analyzed the impact of stress or pressure of fluids on the improvement of quality of the double sheets hydroforming [16]. As can be seen, there is a constant need to improve the technical conditions and methods for execution of the hydroforming process.

This paper gives the analysis of the experimental execution of hydroforming process of welded sheets of two types of materials with different thicknesses. During hydroforming of pieces with defined size and shape, we have measured the working fluid pressure and displacement (expansion) of welded sheets. The experimental results were used in the process of mathematical modeling. Mathematical model for working fluid pressure was obtained for defined conditions of process execution.

2. The hydroforming process

Hydroforming of connected sheets is a technique of forming by effect of fluid pressure in the interior of the welded sheets. Thereby, the sheets are deformed (spread) to the interior shape of the die which defines the shape and dimensions of the finished piece. The hydroforming process of welded sheets is used for making fuel tanks, the car doors, etc.

Execution process scheme is given in four phases, as shown in Fig. 1:

a) Placement of welded sheets into a die (matrix),
b) Activation of pressure and pre-forming,
c) Calibration with final pressure of the fluid,
d) The finished piece is removed from the die.

With this process it is possible to form welded sheets of the same or different material and thickness. For the analysis in this paper, we conducted hydroforming of work element of the defined shape.

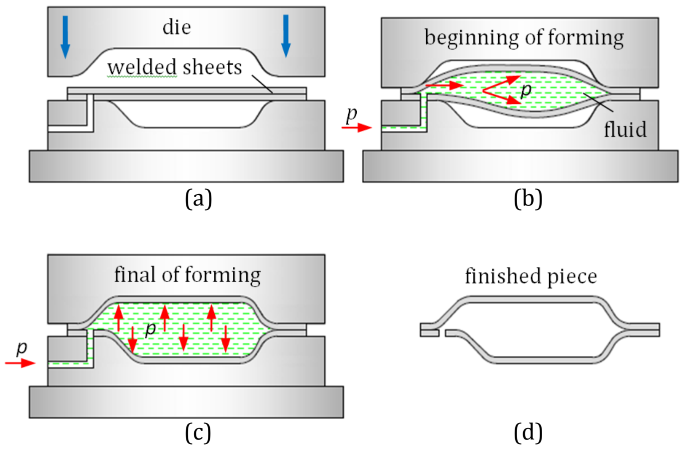


Fig. 1 Scheme of welded sheet hydroforming process

3. Experimental measurement of working fluid pressure

The following parameters were defined for the execution of the experiment:

- Geometrical shape and dimensions of finished pieces,
- Material (sheet) to produce beginning piece,
- Method of sheet welding,
- Tools for hydroforming and fluid,

- Pressure system or measuring amplifier device (pump),
- System for control and measurement of process parameters: computer and measurement equipment for information gathering.

Fig. 2 gives geometric shape and dimensions of the finished piece to be formed [17].

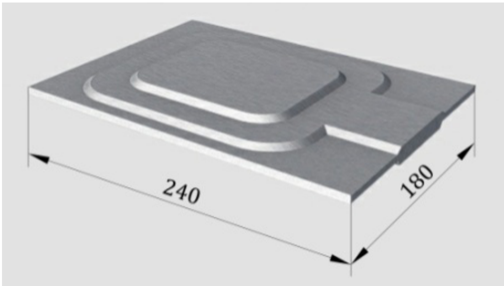


Fig. 2 Geometric shape and dimension of finished piece

3.1 Beginning piece and tools for hydroforming

When producing pieces (beginning piece), two types of materials (sheets) were applied, aluminum (99.5 %) and steel (St 37). Raw parts were produced from cold rolled sheets with thickness: *s* = 1.5 mm and *s* = 2.0 mm. Mechanical properties of the material for raw parts are given in Table 1.

Table 1 Mechanical properties of materials

Types of materials	Yield strength, N/mm^2	Mechanical strength, N/mm^2	Modulus of elasticity, N/mm^2
Steel St 37	235	410	$2.1 \cdot 10^6$
Aluminium 99.5	100	120	$0.7 \cdot 10^4$

MIG welding procedure (protective argon gas) was selected for welding of the two materials.

Fig. 3 depicts the position of raw part in the tool for hydroforming of welded sheets.

Tool for hydroforming of welded sheets was produced from structural steel St 37 and consists of two parts (upper and lower matrix) and connection bolts.

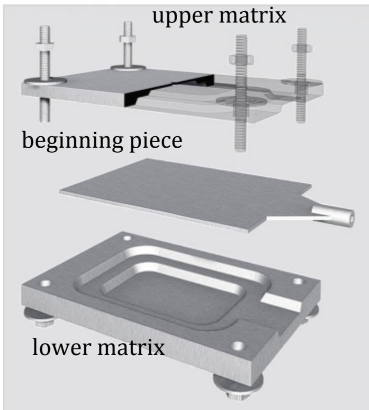


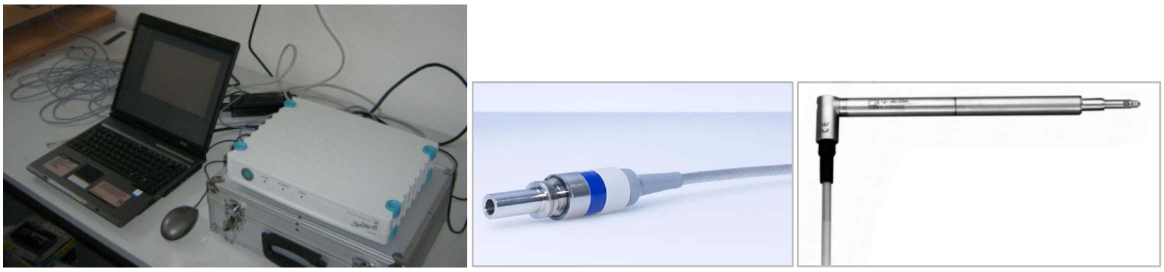
Fig. 3 The position of beginning piece in the tool for hydroforming of welded sheets

3.2. Pump for achieving working fluid pressure

Hydraulic high-pressure pump $p_{max} = 3 \cdot 10^7$ Pa was used for the execution of the experiment. Working fluid for hydroforming is oil *„Inol hidrol-X 46"*, of density 0.884 g/cm^3 (20 °C).

3.3 Measuring equipment

Measuring amplifier device "Spider 8" with eight independent measuring channels was used for the measurement of working fluid pressure and displacement (expansion) of sheets, as shown in Fig. 4.



measuring amplifier device "Spider 8" pressure sensor sensor feed

Fig. 4 Measuring equipment

Applied sensor for the measurement of the working pressure-P8AP, given in Fig. 5, operates on the principle of strain gauges. The nominal sensitivity of the sensor is 2 mV/$5 \cdot 10^7$ Pa. Sensor measuring range is 0-$5 \cdot 10^7$ Pa.

Displacement sensor-WA20, shown in Fig. 4, operates on inductive principle. Nominal sensitivity of the sensor is 80 mV/20 mm. Measuring range of the sensor is 0-20 mm.

Fig. 5 depicts the position of the sensor for measuring fluid pressure and displacement (expansion) of sheets during hydroforming of welded sheets.

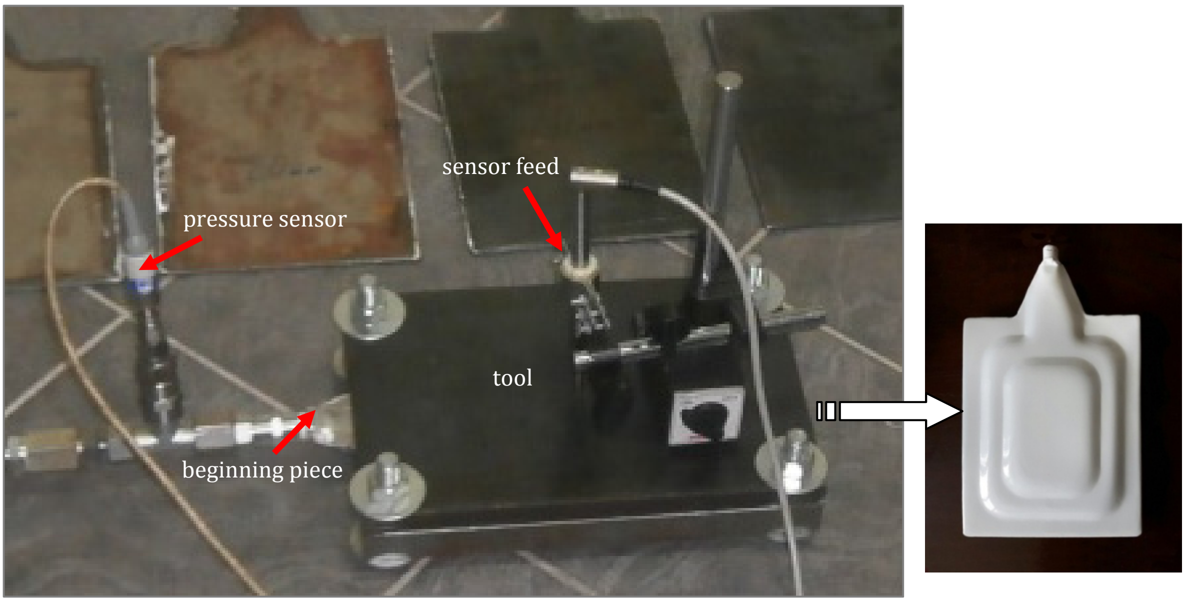


Fig. 5 The position of sensors during hydroforming of welded sheets and shaped piece

3.4 Number of tests in the experiment

Experimental measurements of the defined parameters are aimed at practical application of the results obtained in the planning, design and implementation process. Research and analysis of processes are important for achieving greater process stability in the given circumstances.

Number of probes in this experiment was determined by the rotatable plan of the experiment and expression:

$$N = 2^{k-p} + 2k + n_0 = n_k + n_\alpha + n_0 = 2^2 + 2 \cdot 2 + 5 = 13 \tag{1}$$

where N is total number of experiments, n_k is number of change of variables, n_0 is number of repetitions in plan center, and n_a is number of symmetrically positioned points at plan center. Experiment plan matrix has the shape presented in Table 2. Experiment was conducted in the laboratory of the Faculty of Technical Engineering of the University of Bihac.

Table 2 Experiment plan matrix

Input variables of the process Physical values			Coded values						
Trial No.	Yield strength, N/mm² ($\sigma_{0.2}$)	Thickness, mm (s_i)	X_0	X_1	X_2	$X_1 X_2$	X_1^2	X_2^2	Vector output Y_i
1	100	1.5	1	-1	-1	1	1	1	Y_1
2	235	1.5	1	1	-1	-1	1	1	Y_2
3	100	2.0	1	-1	1	-1	1	1	Y_3
4	235	2.0	1	1	1	1	1	1	Y_4
5	168	1.75	1	0	0	0	0	0	Y_5
6	168	1.75	1	0	0	0	0	0	Y_6
7	168	1.75	1	0	0	0	0	0	Y_7
8	168	1.75	1	0	0	0	0	0	Y_8
9	168	1.75	1	0	0	0	0	0	Y_9
10	263	1.75	1	1.414	0	0	2.0	0	Y_{10}
11	72	1.75	1	-1.414	0	0	2.0	0	Y_{11}
12	168	2.10	1	0	1.414	0	0	2.0	Y_{12}
13	168	1.39	1	0	-1.414	0	0	2.0	Y_{13}

4. Measurement results

Experimental results of working fluid pressure and displacement (expansion) of sheets during hydroforming of welded aluminum and steel sheets, with thickness of 1.5 mm and 2.0 mm, are given in Fig. 6.

Experimental results of working fluid pressure for hydroforming of welded aluminum sheets are given in Fig. 7.

Experimental results of working fluid pressure for hydroforming of welded steel St 37 sheets are given in Fig. 8.

Comparative results of the working fluid pressure for hydroforming of welded sheets of aluminum and steel with 1.5 mm thickness are given in Fig. 9.

Comparative results of the working fluid pressure for hydroforming of welded sheets of aluminum and steel with 2.0 mm thickness are given in Fig. 10.

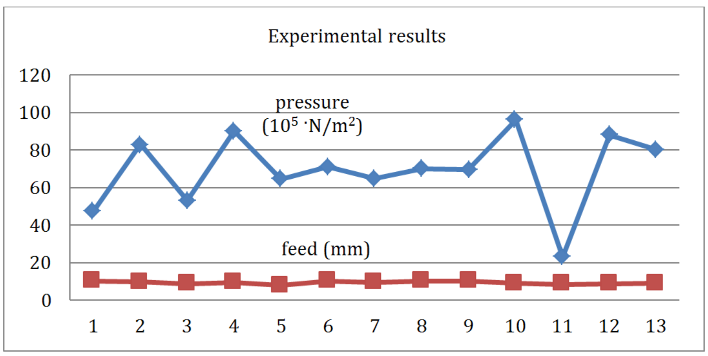


Fig. 6 Experimental results of working fluid pressure and displacement during hydroforming of welded sheets

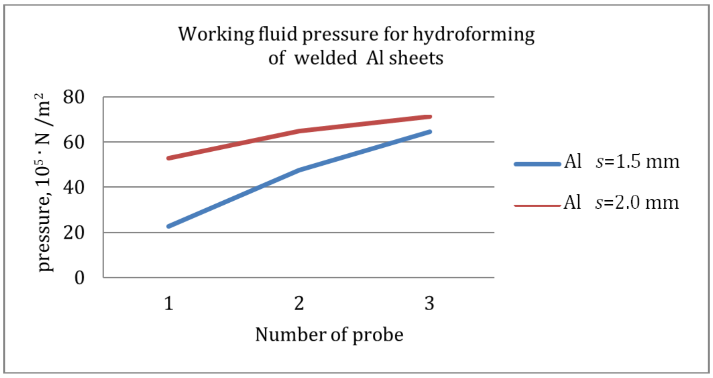


Fig. 7 Working fluid pressure for hydroforming of welded aluminum sheets

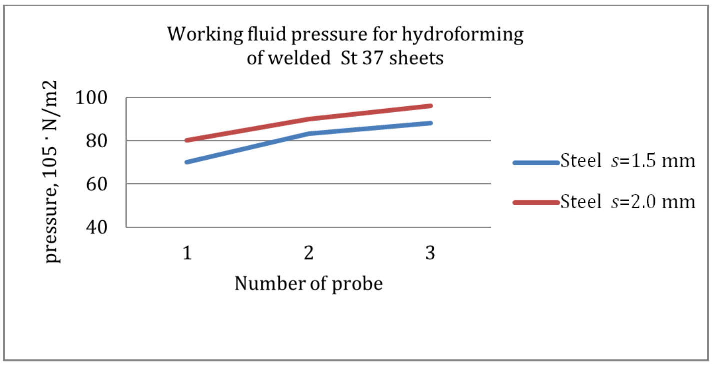


Fig. 8 Working fluid pressure for hydroforming of welded steel sheets

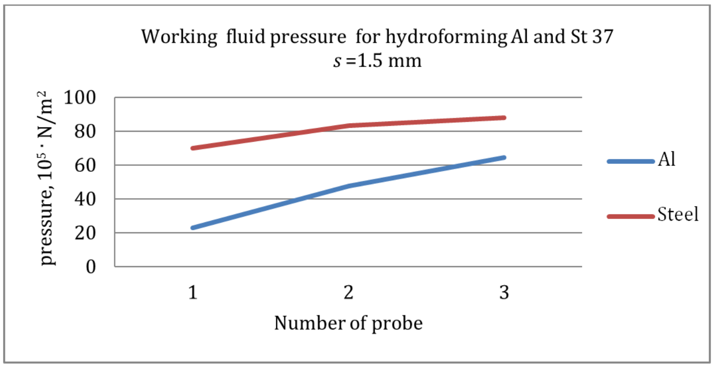


Fig. 9 Comparative results of working fluid pressure for aluminum and steel sheets with 1.5 mm thickness

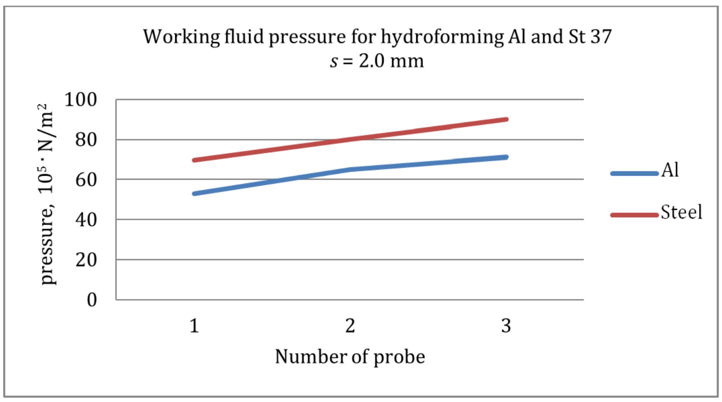


Fig. 10 Comparative results of working fluid pressure for aluminum and steel with 2.0 mm thickness

Analysis of the experiment results

The analysis of the obtained experimental values of the working fluid pressure for 13 samples (welded sheet 1.5 mm and 2.0 mm thickness, aluminum Al 99.5 % and steel St 37) provides the following conclusions:

- Average value of the working fluid pressure to form 2.0 mm thick aluminum sheet compared to the sheet thickness of 1.5 mm is higher for around 10.38 %,
- Average value of the working fluid pressure to form 2.0 mm thick steel sheet compared to the sheet thickness of 1.5 mm is higher for around 7.67 %,
- Increase in the working fluid pressure in both materials is the result of an increase in the thickness of welded sheets,
- The design of welded 1.5 mm thick steel sheet requires higher values of the working fluid pressure for around 42.84 % compared to welded aluminum sheets of the same thickness,
- The design of welded 2.0 mm thick steel sheet requires higher values of the working fluid pressure for around 41.12 % compared to welded aluminum sheets of the same thickness,
- Increase in the working fluid pressure during hydroforming of welded steel sheets is justified due to the differences in the mechanical properties of steel and aluminum,
- Average value of displacement deviations for 13 samples is about 7 %, which is caused by changes in the structure and quality of the sheet.

5. Modeling of working fluid pressure during hydroforming od welded sheets

The measured values of the working fluid pressure and displacement after conducted 13 experiments will be used to define a mathematical model that, in the appropriate level of accuracy, adequately describes the hydroforming process of welded sheets with defined shape and conditions of the process execution.

The model would be used in the design phase of the process, in analyzing and forecasting the state of the process [18].

The analysis of the stochastic process starts from the general functional relationship between the dependent variable size (Y_i) and independent variables (x_i), which can be presented with the model as follows:

$$Y_i = f_{(x_i)} = f_{(x_1, x_2)} \tag{2}$$

$$\text{i.e. } Y = p = f(\sigma_{0.2}, s) \tag{3}$$

Coded values of physical quantities are obtained using the following expressions:

$$X_1 = 1 + 2\frac{\ln\sigma_{0.2_i} - ln\sigma_{0.2_{imax}}}{\ln\sigma_{0.2_{max}} - ln\sigma_{0.2_{min}}};\ X_2 = 1 + 2\frac{\ln s_i - \ln s_{imax}}{\ln s_{max} - \ln s_{min}} \tag{4}$$

Table 3 gives the physical and coded values of input parameters for hydroforming of welded sheets.

Table 3 Physical and coded values of the input variables

Input variables of the process		Coded values				
		-$\sqrt{2}$	-1	0	1	$\sqrt{2}$
Physical values	$x_1 = \sigma_{0.2}$ N/mm^2	72.0	100.0	168	235	263
	$x_2 = s_i$ mm	1.39	1.5	1.75	2.0	2.10

For the analysis of the process, the most commonly used form is polynomial function, so the impact of independent variable parameters onto output variable can be displayed in a polynomial mathematical model of the second order:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \tag{5}$$

Testing the importance of coefficients (b_0, b_1, b_2, b_{12}, b_{11}, b_{22}) and the adequacy of the mathematical model was established with the system of experiment repetition in the central point of the plan.

$$Y = 68.04 + 22.01X_1 + 2.95X_2 - 5.21X_{11}^2 + 7.12X_{22}^2 \tag{6}$$

Testing of adequacy was conducted with mathematical analysis according to F–criterion Fisher. The condition $F_a \leq F_t$ is satisfied.

$$F_a = 5.04 \leq F_t = 9.12 \tag{7}$$

in which F_a – adequacy according to Fisher criterion, and F_t – tabulated values according to Fisher criterion.

Testing the multiple regression coefficients R provided additional adequacy indicator of the obtained mathematical model:

$$R = \sqrt{1 - \frac{\sum_{j=1}^{N}(y_j^E - y_j^R)^2}{\sum_{j=1}^{N}(y_j^E - \bar{y}^E)^2}} = 0.981 \tag{8}$$

in which:
y_j^E – Values of experimental results,
y_j^R – Calculation values of the obtained model, and
$\bar{y}^E = \frac{\sum_{i=1}^{N} y_j^E}{N}$ – Arithmetic mean of all experimental results.

The value of R = 0.981 (0 ≤ R ≤ 1) indicates that the model positively describes the results of the experiment which confirms the interdependence between the input variables and goal functions (working fluid pressure).

The coefficient of determination R^2 is determined by the quality and reliability of the model.

$$R^2 = 0.962 \tag{9}$$

The obtained results of the coefficient of determination R^2 indicate that 96.2 % of the variability is attributed to the operation of the input variables (X_i).

Final, decoded form of mathematical model for working fluid pressure is given in expression:

$$Y = p = -28.55 \ln(\sigma_{0.2})^2 + 348.25 + 338.84 \ln(\sigma_{0.2}) - 362.35 \ln(s) - 820.3 \tag{10}$$

The fluid pressure values obtained by mathematical modeling, in regard to the change of sheet thickness and yield strength, are given in Fig. 11.

Comparative values of fluid pressure obtained by modeling and experimental measurements are presented in Fig. 12.

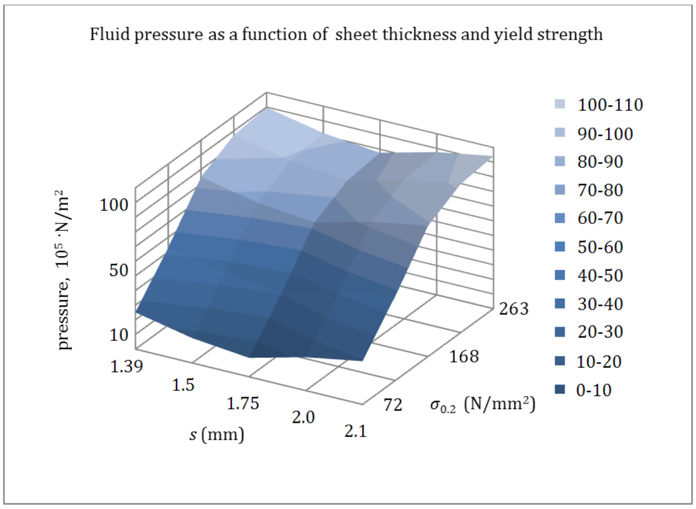


Fig. 11 Chart of the fluid pressure as a function of the sheet thickness and yield strength by model

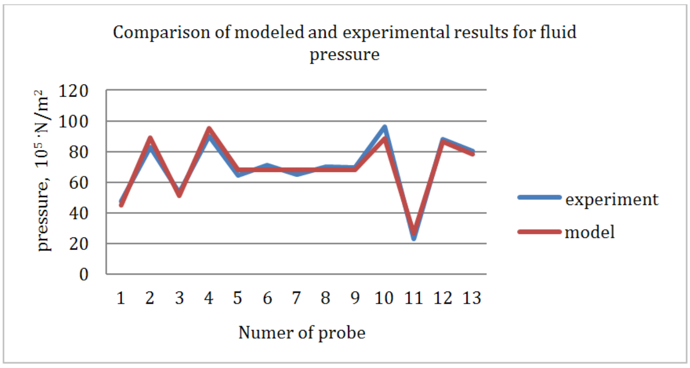


Fig. 12 Comparison of modeled and experimental results for fluid pressure during hydroforming of welded sheets

6. Conclusion

Accuracy, quality and ability to create very complex sheet pieces in one phase justify the fact that about 20 % of the parts in the automotive industry are obtained by applying sheet hydroforming process. The result is an increase in the number of research and development of hydroforming process. Experimental research in the paper aimed to obtain a mathematical model to determine the working pressure of the fluid, which would be applied in the design of hydroforming process of welded sheets of steel St 37 and Al 99.5, with sheet thickness of 1.5 mm and 2.0 mm. Analysis of the results was conducted after planning and execution of the experiment, confirming the influence of mechanical properties of materials (yield strength) and the geometric sizes (thickness of the sheet) on the value of the experimentally obtained working fluid pressure.

The experimental results were applied to mathematical modeling. A series of mathematical verifications referring to the uniformity of results, reliability and checking the adequacy of the mathematical model were conducted in order to obtain the resulting mathematical model.

The quality and reliability of the model has been confirmed by the coefficient of determination, which shows that 96.2 % of the variability is attributed to the influence of input variables, yield strength and thickness of the sheet. Comparative overview of the results (Fig. 12) indicates that the deviation in the values of working fluid pressure obtained by mathematical modeling is very small compared to the values obtained experimentally.

The resulting mathematical model will be used in the design of hydroforming process of welded sheets, and optimization of the working pressure of the fluid.

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