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ANALYSIS OF THE DEPENDENCE OF RESIDUAL STRESSES ON THE STRUCTURAL PARAMETERS OF VESSEL HEADS USING EXPERIMENTAL DESIGN

ANALIZA ZAVISNOSTI ZAOSTALIH NAPONA NA KONSTRUKCIONE PARAMETRE DANCA POSUDA PRIMENOM PLANIRANOG EKSPERIMENTA

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Keywords
- welded pressure vessel heads
- incremental sheet forming
- experimental design
- heat treatment
- residual stress in HAZ

Abstract

The large pressure vessel heads must be made by welding the base sheet in order to achieve the required diameter. The shaping of base sheets by the process of incremental sheet forming (ISF) introduces changes in the surface layers. Intense local plastic deformation creates local residual stresses that, together with the residual stresses from welding, can have a positive or negative effect on the overall stress state of the vessel heads. Using the experiment design, it is possible to make a functional dependence of structural parameters such as yield stress, sheet thickness and diameter with the magnitude of residual stresses. The influence of heat treatment was also taken into the analysis. For the observed process, an experimental design of a four-factor process based on a partial multi-factor orthogonal plan of the first order (semi-replicate) type 24-1 is used.

Ključne reči
- zavarena danca
- inkrementalno oblikovanje limova
- planirani eksperiment
- termička obrada
- zaostali naponi u ZUT

Izvod

Danca posuda pod pritiskom velikih dimenzija moraju biti izrađena zavarivanjem polaznog lima kako bi se ostvario odgovarajući prečnik. Oblikovanjem osnovnih limova postupkom inkrementalnog oblikovanja (ISF) uvode se promene u površinske slojeve. Intenzivna lokalna plastična deformacija izaziva lokalne zaostale napone koji, zajedno sa zaostalim naponima od zavarivanja, mogu imati pozitivan ili negativan uticaj na ukupno naponsko stanje danca posuda. Primenom planiranog eksperimenta moguće je napraviti funkcionalnu zavisnost strukturnih parametara kao što su napon tečenja, debljina i prečnik lima sa veličinom zaostalih napona. U analizu je uzet i uticaj termičke obrade. Za posmatrani proces upotrebljen je eksperimentalni dizajn četvorofaktorskog procesa koji se temelji na parcijalnom multifaktorskom ortogonalnom planu prvog reda (polurepliciranje) tipa 24-1.

INTRODUCTION

The experimental method is one of the basic epistemological scientific methods. Among the main goals of the experimental method is the discovery of cause-and-effect relationships between objects, i.e., necessary states and phenomena. There are four basic elements in the structure of each experiment: object, experimental technique, experimental plan and experimenter /1, 2/. A characteristic of the classic theory of experiment planning is that when examining a phenomenon, only one factor is varied, while the others are kept constant, /3/. This results in a large number of experimental tests and presents difficulties in multifactorial experimental research with the need for a large number of repetitions.

One of the major disadvantages is the impossibility of determining the degree of influence (interaction) of various factors.

The planned experiment is carried out on vessel heads made by incremental plastic deformation process /4, 5/. This procedure is based on the gradual action of the indenter tool over the entire surface of the future vessel heads. The directional action of the tool leads to different properties in the material at the local level which results in a non-uniform distribution of properties. This phenomenon is not favourable from the aspect of safety under the influence of the workload. Different thicknesses of the starting sheets as well as the number of pressing operations can cause different effects in the material, /6/. The number of pressing operations and the size of tool radius have the greatest influence on the magnitude and distribution of residual stresses, /7/.

The aim of the planned experiment presented in this paper is to obtain the interaction of individual analysed factors such as: yield stress of the base material, roundel diameter (starting circular plate), roundel sheet thickness and heat treatment modelled on the observed output size - residual stress, /8/.

In the experimental sense, it is usually very difficult to cover all the parameters that have an influence on certain measured quantities. The reasons for this can be of a financial or real nature. Therefore, it is extremely important to have a good knowledge of the physical process being monitored, so that the total number of experimental parameters selected constitutes an experimental domain on the basis of which a safe scientific opinion can be made about the given process.

METHODOLOGY

The starting pieces are so-called roundels made of sheets from several segments. Rounds are made only for purposes of these tests, and in actual production circumstances they are not made that way. Each roundel is made from a central circular segment and with 12 circular sections that are joined together to form a circular plate-roundel. The central circular segment is not the subject of any analyses. Circular sections are made of material of the same thickness, but of different material quality. A total of 5 segmented vessel heads are made.

The vessel heads are made of three different materials, in three thicknesses and three diameters as follows.
Materials: P 460 NL1 NT; P 355 NL2, and S 235 JR+N.
Thickness: 6 mm; 10 mm; 14 mm.
Diameters: 1500 mm; 2250 mm, and 3000 mm.

Technology of welding samples

The carbon equivalent for selected samples is calculated using the Ito-Bessyo equation, /9/:

$$C_E = C + \frac{Mn}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{V}{10} + \frac{Cu}{20} + \frac{Si}{30} + 5B\,. \qquad (1)$$

The carbon equivalent for the selected samples is given in Table 1. As in all three cases, materials with good weldability are used, welding technology EN ISO 4063-121 (EPP /UP) is used to join the sheets, /10/, Table 1.

Table 1. C-equivalent.

Sheet material and thickness	CE	CE
	According to the certification documentation	According to Eq.(1)
S235×6 mm	0.25	0.25
S235×14 mm	0.26	0.18
P355×10 mm	0.4	0.18
P460×6 mm	0.47	0.26
P460×14 mm	0.52	0.30

Technology of plastic processing

Vessel heads for the experimental research are made by gradual pressing from initial preparations, the so-called roundels, obtained from welded sheets. During such a process of making vessel heads, pressure zones are observed along the radius as a consequence of manufacturing technology with a combination of welding and plastic deformation. It is assumed that the level of residual stresses is significant, especially in the part of the welded joint present in the process of obtaining the roundel. Wavy edges are observed in the case of vessel heads of smaller thickness which are a result of prevented deformation caused by the manufacture of a large number of welded joints. Vessel heads made for experimental research have a large number of segments that are radially welded. Welded joints are stiffer and thicker than the base material which prevents the material from flowing and causes waves to appear at the edges. This phenomenon was not observed with larger sheet thicknesses. The incremental deformation of the roundel is performed on a hydraulic press with an exchangeable tool and pressure force. The press is of the P2MF 200x4 type - Sertom, Milan, Fig. 1.

roundel pressing   final shaping of the torus

Figure 1. Production of vessel heads by incremental deformation.

The goal of experimental analysis, according to which the number of factors, the experimental domain, method of forming the test execution matrix plan, and the specific type of analysis is determined, is to obtain a mathematical statistical regression model that will describe the objective function in a valid way. Table 2 shows the welding procedure.

For the observed process, an experimental design of a four-factor process based on a partial multi-factor orthogonal plan of the first order (semi-replicate) type 2^{4-1} is used. It is considered that there is no *a priori* information about the significance of factor interactions, so the generator, i.e., the contrast which provides such evaluations of effects will be used, whereby basic effects (otherwise combined with higher-order interaction effects) are evaluated separately from first-order interaction effects.

Several output values are set as objective functions. Table 3 shows the number and type of treated parameters in the experimental design.

Table 2. Welding procedure.

Additional and auxiliary material		Preheating temperature	≥100 °C
Name and manufactur.	ESAB Ok Auto rod 13.40	Interlayer temperature	200 °C
Classification	EN14171-A-S3Ni1Mo	PWHT	930 ± 40 °C
Type of lining	÷	work	manual
Wire diameter	∅3.0 mm	Max. pass width / layer number	14 mm/2 for t = 6 mm 15÷17 mm/2 for t = 10 mm 22÷24 mm/2 for t = 14 mm
Drying	2h/350 °C	cleaning	grinding and brushing
Powder	OK-Flux 10.62	other things	÷
Remark	Standard: EN14171-A /11/		

Table 3. Parameters and their levels relevant for experiment design.

Symbol	Meaning	Level 1	Level 0	Level 2	Degree of freedom
R_{eH} (x_1)	Yield strength (MPa)	R_{eH1}	R_{eH0}	R_{eH2}	1
D (x_2)	Diameter (mm)	D_1	D_0	D_2	1
t (x_3)	Thickness (mm)	t_1	t_0	t_2	1
HT (x_4)	Heat treatment	before HT	-	after HT	1

Such are half-replica generators:

$$x_4 = x_1\, x_2\, x_3\,; \quad x_4 = -\, x_1\, x_2\, x_3\,, \tag{2}$$

whose contrasts are:

$$J = x_1\, x_2\, x_3\, x_4\,; \quad J = -\, x_1\, x_2\, x_3\, x_4\,. \tag{3}$$

The overall matrix plan for the execution of the experiment will have the appearance according to Table 4.

Table 4. Global plan matrix - experimental plan.

Block No.	Plan matrix								Code	Results $Y_{i\text{-}j}$
	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$		
Block I	+1	-1	-1	+1	+1	-1	-1	+1	c	
	+1	+1	-1	-1	-1	-1	+1	+1	a	
	+1	-1	+1	-1	-1	+1	-1	+1	b	
	+1	+1	+1	+1	+1	+1	+1	+1	abc	
no	+1	0	0	0	0	0	0	0		
	+1	0	0	0	0	0	0	0		
Block II	+1	-1	-1	-1	+1	+1	+1	-1	(1)	
	+1	+1	-1	+1	-1	+1	-1	-1	ac	
	+1	-1	+1	+1	-1	-1	+1	-1	bc	
	+1	+1	+1	-1	+1	-1	-1	-1	ab	
no	+1	0	0	0	0	0	0	0		
	+1	0	0	0	0	0	0	0		

According to the methodology of collecting measurement data and processing experimental results, a matrix plan for performing experimental tests is defined.

As observed quantity ($Y_{i\text{-}j}$) the value of residual stress measured in the heat affected zone (HAZ) of the butt-welded joint is used, i.e., residual stresses after welding the roundel segments and carrying out the incremental deformation procedure.

Measurement of residual stresses

Measurements of residual stresses were performed using the Hole Drilling Method according to ASTM E837, /12/. The measurements were made in the heat-affected zone which includes a narrow area next to the very edge of the weld. The place of the measuring sensor (strain gauge type 1-RY61-1.5/120) was also chosen in order to determine the residual stress values at places of maximal plastic deformation, that is, the zones with maximum degree of plastic deformation, Fig. 2. The measurement results are shown in Table 5.

Before the final conclusions, it should be noted that measurements were made in the heat affected zone (HAZ) or zones close to the HAZ with a relatively small number of measurements for this type of analysis. The values of the main residual stresses, using Mohr's circle equation, were recalculated so that they follow the directions of the main operating stresses in the meridional and circular directions. The residual stress in the circular direction σ_ϕ was used for further analysis in structural integrity assessment.

Figure 2. Strain gauge location on the vessel head.

Experimental procedure

Table 5 shows the results of conducting the experimental procedure on the basis of the defined experimental plan shown in Table 4, i.e., displays the required output values for corresponding positions of points in the experimental plan, /8/.

Table 5. Plan matrix of experimental procedure.

Block / HT	Factors							Output function Y
	Exp. no	X_1	R_{eH} (MPa)	X_2	D (mm)	X_3	T (mm)	S_{RFS} (MPa)
1-before HT	9	-1	S235	-1	1500	1	14	181
	5	1	P460	-1	1500	-1	6	234
	10	-1	S235	1	3000	-1	6	131
	6	1	P460	1	3000	1	14	102
	1	0	S355	0	2250	0	10	305
	2	0	S355	0	2250	0	10	337
2-after HT	11	-1	S235	-1	1500	-1	6	103
	7	1	P460	-1	1500	1	14	100
	12	-1	S235	1	3000	1	14	168
	8	1	P460	1	3000	-1	6	148
	3	0	S355	0	2250	0	10	171
	4	0	S355	0	2250	0	10	168

Based on the plan-matrix of the derived experimental design, mathematical modelling of the vessel heads incremental production process was performed within the limits of experimental design determined by specified levels of experiment factors. The MATLAB® /13/ software with the Model Based Calibration Toolbox module is used for statistical regression and dispersion analysis of the experimental results.

For the basic three factors as input parameters R_{eH}, D, and t, where the natural logarithm function is applied as a transformation function with regard to the assumed complex polynomial mathematical model of the function, the requested S_{FRS} output size is obtained depending on the input parameters:

$$S_{RFS} = C \cdot R_{eH(OM)}^{\beta_1} \cdot D^{\beta_2} \cdot t^{\beta_3}\,. \tag{4}$$

In order to translate the complex mathematical model of the observed process into a quasi-linear model suitable for carrying out the planned experiment, as well as regression and dispersion analysis, the principle of logarithmisation is applied, and the following form is obtained:

$$\ln S_{RFS} = \ln C + \beta_1 R_{eH(OM)} + \beta_2 D + \beta_3 t \,. \tag{5}$$

By replacing the members shown above in the form:

$$y_4 = \ln S_{RFS};\; b_0 = \ln C;\; b_1 = \beta_1;\; b_2 = \beta_2;$$
$$x_1 = \ln R_{eH(OM)};\; x_2 = \ln D;\; b_3 = \beta_3;\; x_3 = \ln t \,, \tag{6}$$

formally a linear form is obtained:

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \,. \tag{7}$$

In the case of applying encoded values of variables, an encoding expression of the following form is applied:

$$x_i = 1 + 2\frac{\ln X_i - \ln X_{i\max}}{\ln X_{i\max} - \ln X_{i\min}} \,. \tag{8}$$

The average level of the physical value is determined by the expression:

$$X_{isr}^2 = X_{i\min} \cdot X_{i\max} \,. \tag{9}$$

On the basis of the presented theoretical approach for the application of planned experimental design, a preliminary investigation of the form and degree of the polynomial function for describing the process is applied, and the fact is reached that, in general, the polynomial expression of the second degree describes observed processes well enough, and the expression is of the following form:

$$\hat{y} = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 +$$
$$+ b_{23} x_2 x_3 + b_4 x_1^2 + b_5 x_2^2 + b_6 x_3^2 \,. \tag{10}$$

The convenience of using the module for experimental research of MATLAB® software lies in the fact that the creation of a regression model can be done with real parameters, as well as with coded values.

For the analysis of the relationship between 3 input parameters (R_{eH}, D, t) and the output quantity - objective functions (S_{RFS}) the same initial form of the regression model of linear form is used, and optimisation is carried out through the later 'stepwise' analysis regression model and number of parameters.

Analysis of the results for measured residual stresses

As the first output function of the goal, the dependent function S_{RFS} is analysed - values of residual stress in the measuring points of the experimental model.

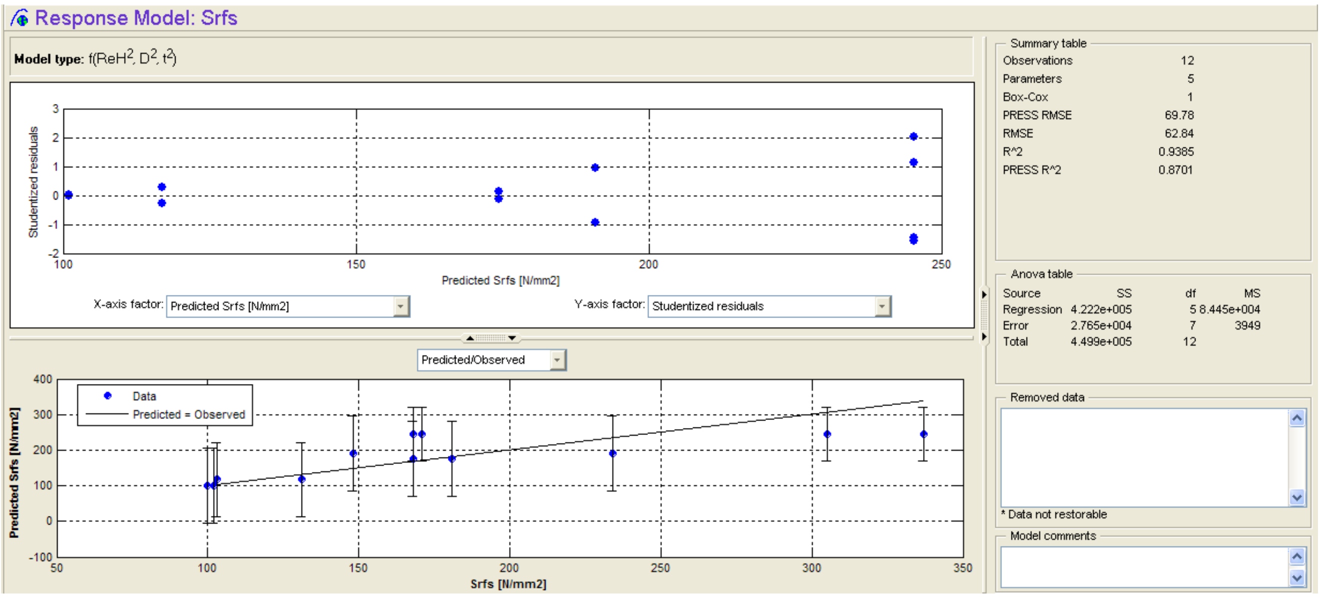


Figure 3. Agreement of real data and regression model.

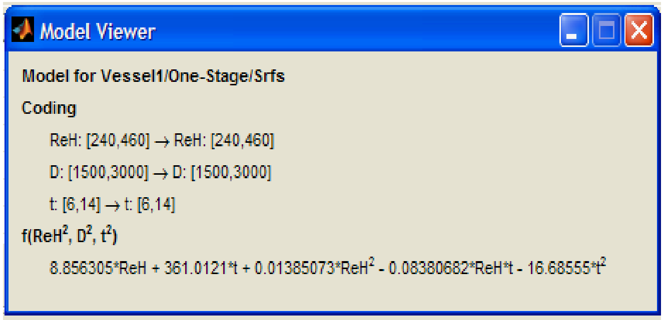


Figure 4. Presentation of the regression model.

Figure 3 shows values of residuals, as well as the 'predicted/observed' relationship which shows a solid agreement between the mathematical expression and real values, and Fig. 4 shows the regression model that describes the dependence of the output function on input parameters.

From the regression model, a very significant influence of parameter t and the influence of parameter R_{eH} is visible, while, for example, it is shown that parameter D is insignificant for observing the output value of residual stresses.

The form of regression model shown above is applied to a 'stepwise' analysis in several steps, on the basis of which the final form of regression equation is arrived at while reducing the number of non-influential parameters, using the Min PRESS option.

Based on the 'stepwise' analysis, the final mathematical form of regression equation is created which describes the considered process with sufficient reliability.

$$y = 8.856305 \cdot R_{eH} + 361.0121 \cdot t + 0.01385073 \cdot R_{eH}^2 -$$
$$-0.0838 \cdot 0682 R_{eH} \cdot t - 16.68555 \cdot t^2 \,. \tag{11}$$

The coefficient of determination is $R^2 = 0.9385$, Fig. 3.

The statistical characteristics of the regression model PRESS RMSE, RMSE, R^2 and PRESS R^2 indicate a satisfactory match between the real data of the experiment and the 'predicted' data, i.e., data obtained by recalculation according to the regression mathematical model for each experimental point of the plan matrix of the experimental design.

It can be seen from the mathematical expression of the regression model that, in relation to the initial settings of the polynomial model, some variables are excluded because the dispersion analysis concludes that their influence is insignificant, and they can be omitted from the regression formulation of the observed process, such as, for example, parameters D, D^2, relations $R_{eH} \times D$, and $D \times t$.

Figure 5 shows the 'surface response' for the combination of influential treated parameters of the $R_{eH} \times t$ experiment, where the spatial-surface representation of the change in value of output variables depending on the combination of parameters is given.

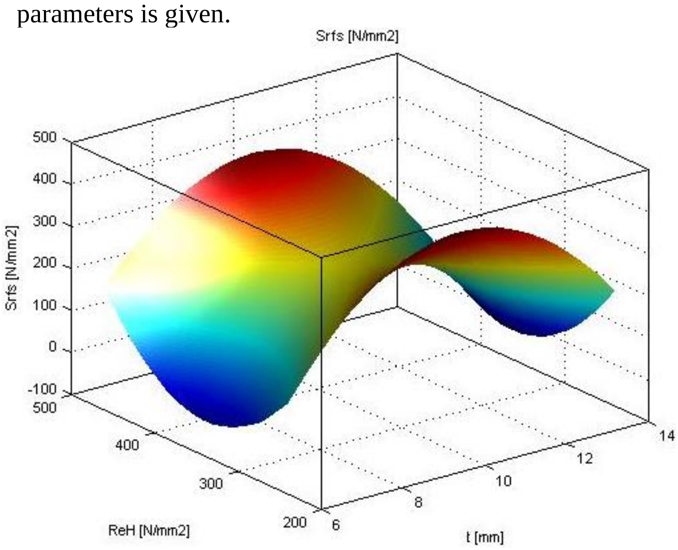


Figure 5. 'Surface response' diagram for corresponding $R_{eH} \times t$ parameter relationships.

Figure 6 shows the contour plot of the dependence of output size on treated parameters in different combinations of their values, which shows the influence of the observed parameters R_{eH} and t.

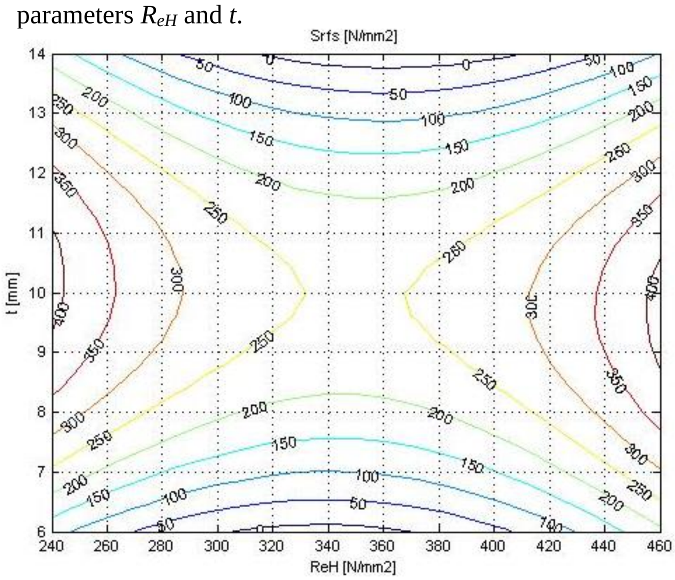
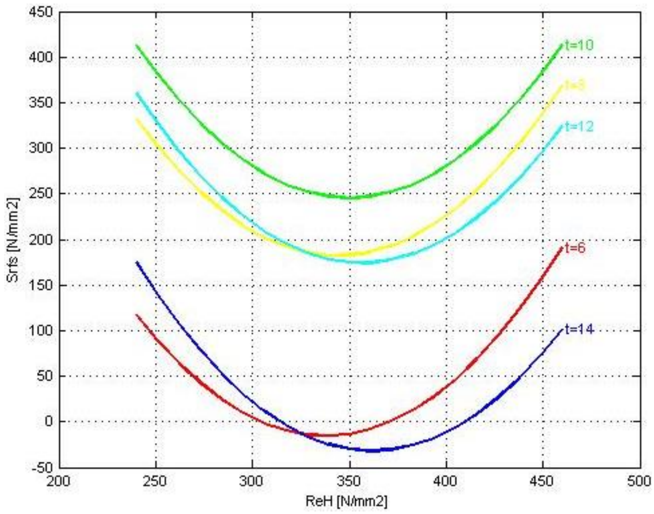
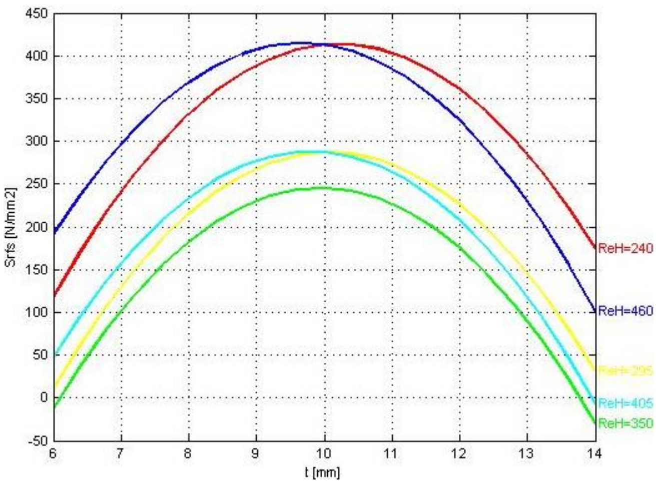


Figure 6. 'Contour plot' display for corresponding parameter relationships.

Figure 7 shows the 'multiline plot' option, where the curve dependence of output size on treated parameters in individual combinations is given, i.e., in the combination influencing the output function.



a) $R_{eH} \times t$ multiline plot



b) $t \times R_{eH}$ multiline plot

Figure 7. Diagram 'multiline plot'.

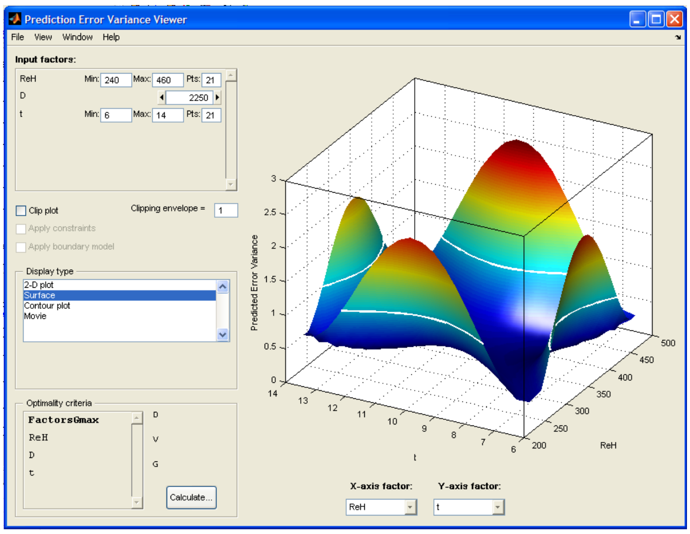


Figure 8. Display of the error variance of the experiment for observed parameters.

The ‘multiline plot’ dependency display option is a very useful tool in assessing the magnitude of the influence of individual parameters and their interrelationship values on the output observed value, i.e., the objective function.

From the position of lines in the simultaneous influence of the combination of two factors on the objective function in Fig. 7, it can be concluded that the interaction between parameter R_{eH} and parameter t exists, which confirms their inclusion in the regression model of the objective function. Analogously, on the diagram in Fig. 8, it can also be concluded that the influence of thickness ‘t = 10 mm’ on the value of residual stresses is particularly pronounced at values of R_{eH} = 240 and 460 N/mm^2.

ANALYSIS OF RESULTS

As a basis for conducting experimental research, the matrix plan of the experimental design type 2^{4-1} is used. On the basis of conducting measurements based on the implemented experimental plan, Table 4 shows the results of the planned experimental procedure, that is, displays of the required output values for corresponding positions of points of the experimental plan. Input parameters that are varied are R_{eH} - yield stress of sample base material, D - diameter of vessel heads, t - thickness of vessel head sheets. The output value that was measured experimentally is S_{RFS} - value of residual stresses.

Based on the assessment of approach for the application of planned experimental design, a preliminary investigation of the form and degree of the polynomial function for describing the process is applied, and it is concluded that, in general, a polynomial expression of the second degree describes the observed processes well enough. This proves to be adequate for most, but not all, objective output functions.

For the analysis of the relationship between the 3 input parameters (R_{eH}, D, t) and output quantity - the objective function (S_{RFS}), the same initial form of the regression model of linear form is used, and through the later ‘stepwise’ analysis, the optimisation of the regression model and the number of variables is performed.

In the analysis of the first output function S_{RFS}, the values of residuals, as well as the ‘predicted/observed’ relationship shows a satisfactory agreement between the mathematical expression and real values, and the regression model describing the dependence of the output function on input parameters proves to be reliable. With the application of ‘stepwise’ analysis in several steps, the final form of the regression equation is reached with the reduction of the number of non-influential parameters, using the Min PRESS option. The coefficient of determination is $R^2 = 0.9315$.

The regression model shows a very significant influence of parameter t, which increases the value of residual stresses as it increases, and the influence of parameter R_{eH} is also significant to a certain extent, while, for example, it is shown that parameter D is insignificant for observing the output value of residual stresses.

From the mathematical expression of the regression model, it is shown that in relation to the initial settings of the polynomial model, some variables are excluded, because the dispersion analysis concludes that their influence is insignificant, and they can be omitted from the regression formulation of the observed process, such as, for example, parameter D, parameter D^2, relations $R_{eH} \times D$, and $D \times t$.

During the analysis, representations of diagrams ‘contour plot’, ‘multiline plot’ and ‘surface response’ of the dependence of the output size in relation to the treated variables in different combinations of their values are given, which of course shows the influence of the observed parameters R_{eH} and t. The ‘multiline plot’ dependency display option is a very useful tool for viewing the size of the influence of individual variables and their interrelationship values on the output observed size, i.e., the objective function.

From the position of lines of the simultaneous influence of the combination of two factors on the objective function on diagrams, it can be concluded that the interaction between parameter R_{eH} and thickness t exists, which confirms their inclusion in the regression model of the objective function. Analogously, on the ‘multiline plot’ diagram, it can also be concluded that the influence of thickness ‘t = 10 mm’ on the value of residual stresses is particularly pronounced at values of R_{eH} = 240 and 460 N/mm^2. Otherwise, the diagrams are displayed in the way two variables change, while the third is kept at an intermediate level.

CONCLUSIONS

By applying the planned experiment, results are obtained that have practical significance for improving the technology of plastic moulding of dished ends.

According to the conducted statistical patterns, the diameters of vessel heads can be excluded in further analyses as a parameter that has no significant influence on the size of the residual stress in the welded vessel head, while the influence of sheet metal thickness and the quality of the material is very significant.

Another important parameter is the welding technology which should be given special attention because it is the cause of bad behaviour of the entire structure. Namely, the heat affected zone proves to be a weak spot.

This structural analysis is also justified from the economic point of view, because it is possible to avoid unnecessary heat treatment without jeopardising the vessel head strength.

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REFERENCES

1. Montgomery, D.C., Design and Analysis of Experiments, 10th Ed., Arizona State University, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2019.
2. Jurković, M. (Ed.), Matematičko modeliranje inženjerskih procesa i sistema (*Mathematical modelling engineering of process and systems*), University of Bihać, Faculty of Mechanical Engineering, 1999. ISBN 9958-624-04-4 (in Croatian)
3. Stanić, J., Metod inženjerskih merenja (*Method of engineering measurements*), University of Belgrade, Faculty of Mechanical Engineering, Belgrade, 1990. ISBN 86-7083-014-0 (in Serbian)
4. Matsubara, S. (1994), *Incremental backward bulge forming of a sheet metal with a hemispherical head tool-A study of a*

numerical control forming system II, J Jap. Soc. Technol. Plast. 35(406): 1311-1316.
5. Iseki, H., Kumon, H. (1994), *Forming limit of incremental sheet metal stretch forming using spherical rollers*, J Japan Soc. Technol. Plast. 35: 1336-1341.
6. Vukojević, D., Vukojević, N., Lemeš, S., Ištvanić, Z. (2007), *Analysis of tool radius on vessel head quality made by incremental plastic deformation*, In: Proc. 11th Int. Research/Expert Conf. 'Trends in the Development of Machinery and Associated Technology', TMT 2007, Hammamet, Tunisia, 2007, pp.87-90.
7. Vukojević, D., Vukojević, N., Hadžikadunić, F., Ištvanić, Z. (2007), *Some aspects of spherical vessel head quality made by incremental deformation treatment*, In: Proc 5th Research/ Expert Conf. Quality 2007, pp.299-304.
8. Ištvanić, Z., *Contribution to the assessment of integrity of cylindrical dish ends made by the incremental sheet metal forming* (in Bosnian), Doctoral Dissertation, University of Zenica, Bosnia and Herzegovina, 2022.
9. Alhassan, M., Bashiru, Y. (2021), *Carbon equivalent fundamentals in evaluating the weldability of microalloy and low alloy steels*, World J Eng. Technol. 9(4): 782-792. doi: 10.4236/wjet.2021.94054
10. EN ISO 4063:2009. Welding and allied processes - Nomenclature of processes and reference numbers (ISO 4063:2009, Corrected version 2010-03-01; EN ISO 4063:2010).
11. EN14171: 2002. Welding consumables. Wire electrodes and wire-flux combinations for submerged arc welding of non-alloy and fine grain steels.
12. ASTM 837:2013. Standard test method for determining residual stresses by the hole-drilling strain-gage method.
13. MATLAB (2016), 1994-2023 The MathWorks, Inc., USA. Standards.