Establishing the Optimum Welding Procedure for PE 100 Polyethylene Pipelines Using the Response Surface Design

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The paper presents a modern method to optimize welding procedures for PE 100 polyethylene pipelines using computer-assisted design of experiments. The design of experiments method RSD (Response Surface Design) was applied for optimizing the heated tool butt-welding of PE 100 type polyethylene pipes meant for pressure pipelines. Experimental researches made on 110mm diameter pipes had in view the mathematical modelling of the welding process, so that, on the basis of a number of 32 welding technological versions made, the optimum welding procedure was established, a procedure that met all the imposed conditions.

Keywords: Optimizing, heated tool welding, polyethylene PE 100

The development of thermoplastic materials (polyethylene, polypropylene, polymerized vinyl chloride) had a special amplitude in the last 50 years. One of the most important fields they are applied to is that of pipelines meant for the transport of pressure fluids [1, 2].

At present, at world level, polyethylene pipes and fittings used for this application are of two types: PE 80 and PE 100.

The PE 100 polyethylene type materials meant for pressure pipelines are characterized through a higher cost - performance ratio than that of classical plastic materials, a very good corrosion resistance and long time in service resistance, the service estimated life is 50 years [3 - 5].

Being a thermoplastic material, the PE 100 polyethylene gives very good welding capabilities - the welded joints resistance being at the level of the base material, and, on the other hand, as it assures the inhibition of the rapid crack propagation, there comes the higher reliability in service [6, 7].

The welding processes belong to the category of complex technological systems, characterized by a great number of independent variables, with incomes, influence factors (controllable, disturbing) and outcomes (answer functions) [8, 25].

The optimization of the welding processes supposes a large volume of work and resources higher as the number of variables is higher. A modern alternative of the classic mode to accomplish the optimization of industrial processes is represented by the computer assisted planning of experiments [9, 10].

The planning of experiments represents in fact a series of tests, which aim is to modify the variables of the process (controllable factors) so that the modifications appearing in the process answer could be watched (figure 1) [11, 12].

The paper presents the results of experimental researches made by planning of experiments, to establish the optimum welding procedure for heated tool butt – welding of polyethylene pipes of the PE 100 type and dimensions ø110x10mm, standard dimensional ratio SDR 11.

Due to certain influences which can take place during the welding processes, it is possible that the mechanical properties and geometrical characteristics of welded joints have values situated outside the admitted limits [13]. So, it is compulsory that the welding parameters, and procedures to be checked and optimized [14, 15].

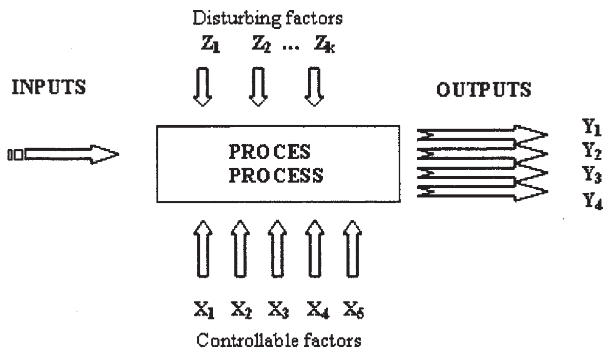

Fig. 1 Model of the welding process

The optimization of the welding procedures supposes the setting of controllable factors values which offer the best answer to the system, for a certain objective. In these cases non-linear experiments can be used as Response Surface Design (RSD) [16]. This type of experiments is also known as superior order non-linear factorial experiments.

One of the most frequently used types of RSD experiments is the central - compound one (composite), which can be complete or fractionary.

In this case, the planning of experiments was realized with an adequate planning and statistic calculus program (MINITAB) considering a RSD central – compound fractionary type (half of it).

Experimental part

In order to make an analysis to establish the optimum welding procedure for PE 100 polyethylene pipes the important elements in defining this material were considered:

-the minimum required strength (MRS) and the melt flow rate (MFR).

Table1, according to standard ISO 4437, presents the values of the inferior safety limit (LCL) and the minimum required strength (MRS), respectively for the PE 100 material used during researches.

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Table 1
LCL AND MRS VALUES FOR PE 100 POLYETHYLENE PIPES

Designation	LCL (20 °C, 50 years) (MPa)	MRS (MPa)
PE 100	10,0...11,19	10,0

The standard DVS 2207/1 presents the range of melt flow rate values (MFR), stipulating that the materials having MFR values = 0.2 – 1.7 g/10 min can be welded together.

The melt flow rate (MFR) has an important role in welding PE 100 polyethylene pipes, so that for different PE 100 material types (and different values of the MFR index), by using the same set of welding parameters can be obtained widths and shapes of the interior and exterior semi burrs which are not in the admissible limits of the standard DVS 2202-1 [17].

So, for a certain PE 100 material with a given value of the melt flow rate, the variation of the welding parameters can lead to modifications in relatively large limits of the geometrical characteristics of the welded joint, in same loading cases even the fracture of the welded joint can be possible [18-21]. This is the reason why it is necessary to establish corresponding values of parameters used and the optimization of welding procedures.

With a view to plan the experiments the controllable factors and the target functions have been established.

In this sense the following elements have been established (according to fig.1):

a)controllable factors (X_1 X_2, ...X_5)
- X_1 is temperature of the heated element (T)
- X_2 - heating time (t_1)
- X_3 - maintenance time (t_2)
- X_4 - welding time (t_5)
- X_5 - heating pressure (P_1)

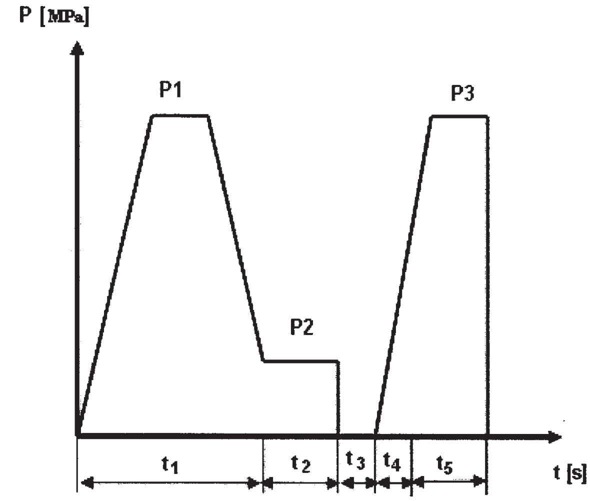


Fig. 2 Welding diagram

b)target functions (Y_1, Y_2 Y_3 Y_4)
- Y1 is tensile fracture resistance of the welded joint (RezTrac)
- Y2 - bending angle on the mandrel (Angle)
- Y_3 - width of the burr (LatBav)
- Y_4 - shape of the burr (FormBav).

The heated tool butt welding was realized with a hydraulic driven semi mechanized welding equipment, according to the welding diagram pressure - time presented in figure 2.

Table 2
TECHNOLOGICAL VERSIONS

No.	Heating pressure P_1 (MPa)	Heating time t_1 (s)	Maintaining time t_2 (s)	Welding time t_5 (s)	Temperature heated element T (°C)
1	2.0	30	80	780	200
2	2.0	20	110	395	215
3	0.6	20	110	395	215
4	1.3	20	110	395	215
5	1.3	20	110	10	215
6	2.0	10	140	780	200
7	0.6	30	140	780	200
8	1.3	20	110	395	215
9	1.3	20	80	395	215
10	2.0	10	80	780	230
11	1.3	20	110	395	230
12	1.3	20	110	395	215
13	1.3	20	110	395	215
14	0.6	10	140	10	200
15	2.0	30	140	780	230
16	2.0	30	80	10	230
17	0.6	10	80	780	200
18	2.0	10	80	10	200
19	1.3	30	110	395	215
20	0.6	10	80	10	230
21	0.6	30	80	10	200
22	1.3	20	110	395	215
23	2.0	30	140	10	200
24	1.3	10	110	395	215
25	0.6	10	140	780	230
26	1.3	20	140	395	215
27	1.3	20	110	780	215
28	2.0	10	140	10	230
29	0.6	30	140	10	230
30	1.3	20	110	395	200
31	0.6	30	80	780	230
32	1.3	20	110	395	215

Values of the welding parameters: temperature, pressure and time have been established at the recommendations of the welding equipment producer.

So, through the variation of welding parameters between certain minimum and maximum limits 32 technological welding versions have been established (table 2).

On the basis of these welding regimes welded probes from pipes were made of PE 100, φ 110 x 10 mm, SDR 11 were realized. For all the 32 probes the necessary stages in the preparation and those corresponding to the heated tool butt welding were rigorously respected [22, 23].

Results and discussions

The control of welded joints was made according to the requirements of the Technical Prescriptions ISCIR CR 7/3 (National Authority for the Control and Approval of Boilers and Pressure Vessels), the samples of the welded joints were subjected to mechanical testing and macroscopic analysis; their mark correspond to probes 1-32.

In the case of tensile testing made on welded joints samples corresponding results have been obtained (presenting fracture in the base material). For bend testing not corresponding results have been obtained, (fracture in the weld) at the following samples of the technological versions 3, 7, 8, 11, 14, 17, 20, 21, 25, 29 and 31:

Bend testing samples with fracture in the weld – 3I1-I4, 7I1-I4, 8I2, 11I2, 14I1-I4, 17I1-I4, 20I1-I4, 21I1-I4, 25I1-I4, 29I1-I4, 31I1-I4 (fig. 3).

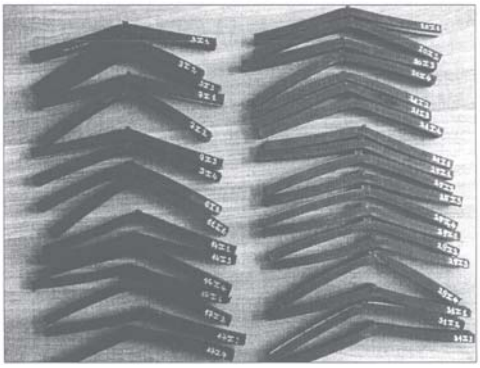


Fig. 3 Bend testing samples with fracture in the weld - probes 3, 7, 8, 11, 14, 17, 20, 21, 25, 29 and 31

From the results of the macroscopic analysis it can be noticed that at welded joints (probes 3, 7, 14, 17, 20, 21, 25, 29 and 31) the shape of the burr both at the interior and at the exterior is sharp with small sizes, generally insufficiently formed (table 3 - for example probe no. 29).

This underlines the fact that for these technological versions the heating pressure and/or heating time had too low values (table 2), which led to welded joints with not corresponding resistance and ductility.

For all the cases, analysing the fracture surfaces there comes out the observations that the embedment of component materials was realized only partially, on certain zones, from the total of surfaces to be joined.

It was found that fracture presents in all cases a brittle character. Even in the case of versions 8 and 11, where both at the interior and exterior burr fractures have been found when bend testing the welded joint.

In all these cases, where the heating pressure, sometimes doubled by the heating times with too low values, the bend testing samples, with the mandrel on the interior or exterior side of the pipe cracked at angles smaller than 160°, the value being in all cases of 150°.

On the bases of results obtained by experiments and controls made, the mathematical modelling of the welding process was possible.

Processing these data on PC, the soft realizes a nonlinear mathematical model, by which the weight of controllable factors and their interactions are established. The welding process is considered well approximated by the model, if the approximation degree given by the index R^2 (R-sq) has values higher than 85%.

In the case of the analysis made, for example for the objective function – bending angle, a good approximation of the welding process was obtained, the value of the index R^2 being 82%.

The significant influence of controllable factors is evinced by the probability p (the most frequently used threshold by statistics being 0.05 respectively 5%). This p means the probability to be wrong appreciating that the respective factor has not a significant influence (or in other words the values $p<0.05$ evince a significant influence of the factor or of the interactions between factors) [24].

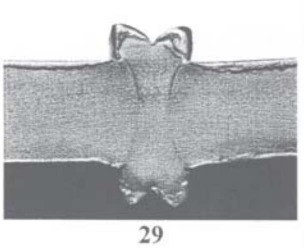
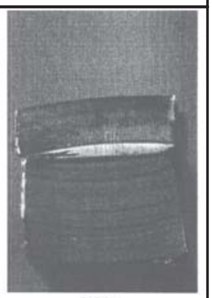
In the case of the analysis realized for objective functions – width of the burr and the shape of the burr it was obtained a very good approximation of the welding process, the value of the index R^2 being 90%, for the first function, respectively 98% for the second objective function.

Following the statistic processing of the experimental data there have been obtained values of probability $p < 0.05$ of the following controllable factors – heating time t_1, maintaining time t_2, heating pressure P_1 and the welding time t_5,:

-temperature T and interaction T*T, for the objective function width of the burr

-pressure P_1 and maintaining time t_2, respectively interactions P_1*P_1, t_2*t_2, P_1*t_5, P_1*T for the objective function shape of the burr.

Table 3
EXPERIMENTAL RESULTS TECHNOLOGICAL VERSION NO. 29

PROBE mark-sample macroscopic analysis	c_{ef} (mm)	b (mm)	Imperfections according to CR 7 / 3	R_{mf} (N/mm²)	α (°)	Fracture surface bend testing sample
 29	3,1	Not formed	Sharp reinforced interior burr	22,75	150	 29I2

c_{ef} - minimum width of weld;
b - exterior burr width;
R_m - fracture strength;
α - bending angle on the mandrel;
I - bend testing sample.

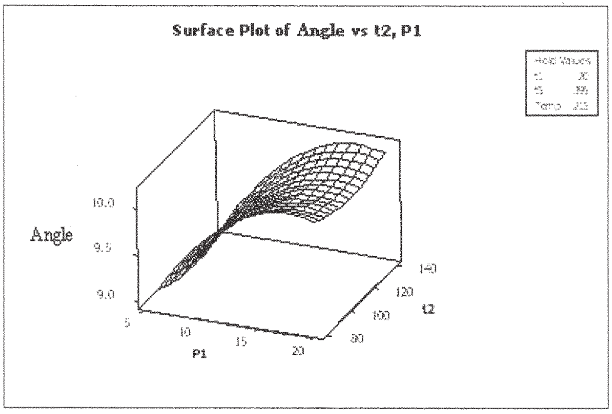


Fig. 4 Dependence: bending angle as a function of time t_2 and pressure P_1

These influences can be evinced under the form of three-dimensional diagrams, too. Figures 4 and 5 present the influences of two controllable factors on the function bending angle on the mandrel.

The mutual dependences can be also graphically presented under the shape of level curves. As an example, two of these are presented below.

The level curves in figures 6 and 7 have been traced by maintaining constant the values of the following parameters: t_1 = 20 s, t_5 = 395 s, T = 215 °C and respectively P_1 = 1,3 MPa, t_2 = 110 s, T = 215 °C.

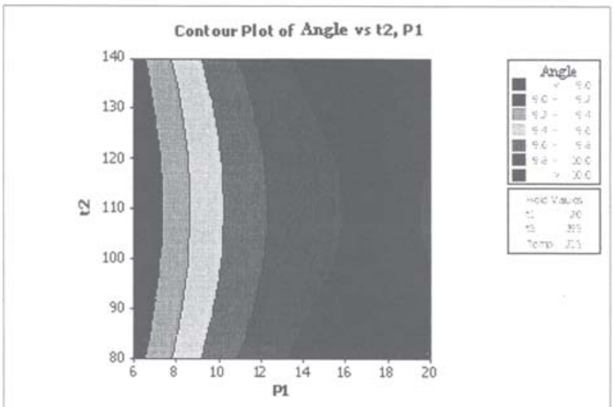


Fig. 6 Level curves: Bending angle as a function of time t_2 and pressure P_1

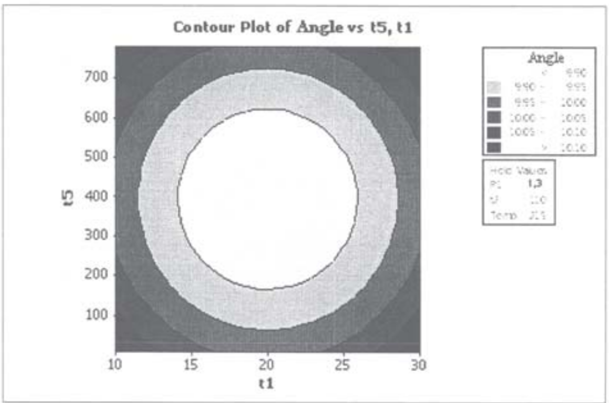


Fig. 7 Level curve: Bending angle as a function of time t_5 and t_1

The similar method was used for the other objective functions. The level curves allow the understanding of the optimisation direction, but only for certain combinations of parameters. The final optimization was realized by software, considering all the analysed welding parameters.

Overlapping the diagrams of the level curves for all objective functions, in the case of parameters P_1 - t_2 (fig. 8)

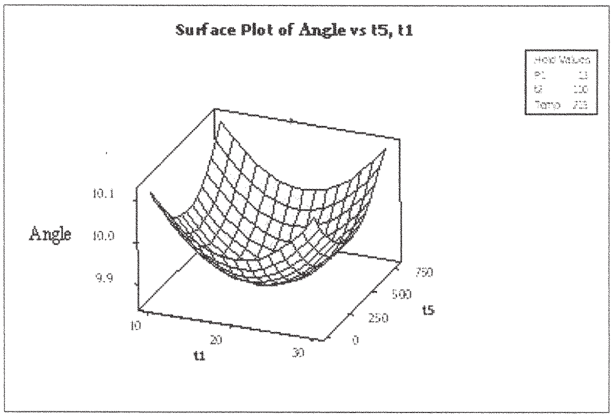


Fig. 5 Dependence: bending angle as a function of time t_5 and t_1

and t_1 - t_5 respectively (fig. 9), the optimum values can be obtained (the white zones in the two figures), on the basis of experimental results.

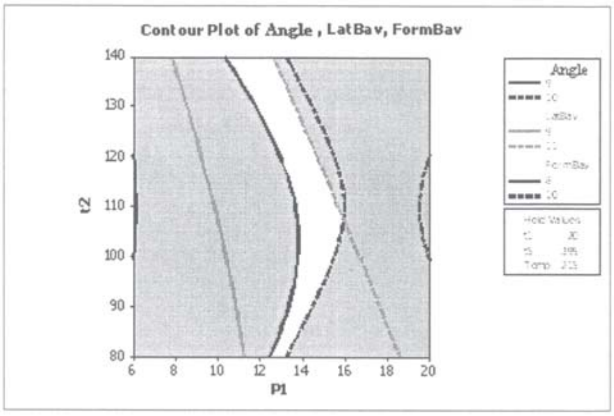


Fig. 8 Optimum zone: Objective functions = f (t_2, P_1)

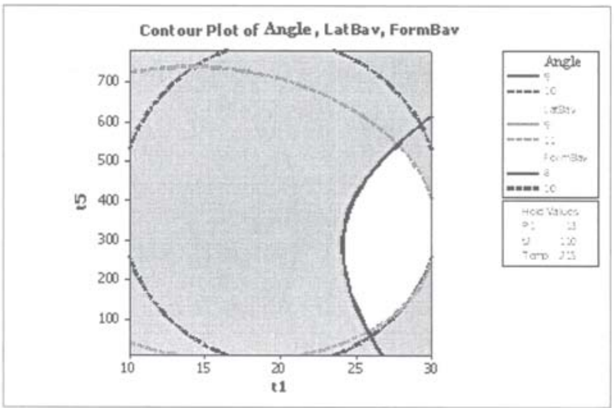


Fig. 9. Optimum zone: Objective functions = f (t_5, t_1)

Process optimization has been made on the basis of mathematical models obtained for each objective function.

In order to optimize answers, for each objective function the following have been established:

- fracture resistance – minimum value 21.85 N/mm^2 (representing 0.95 R_{MB}), and a target value 23 N/mm^2; R_{MB} - fracture resistance of base material.
- bending angle – minimum admissible value 160 °.
- width of the burr – minimum value 8 mm, respectively maximum value 12 mm and a target value of 10 mm.
- shape of the burr – was considered according to a value scale from 1 to 10, the value of 10 corresponding to an ideal shape. The minimum admissible value was 8 and the optimization target was 10.

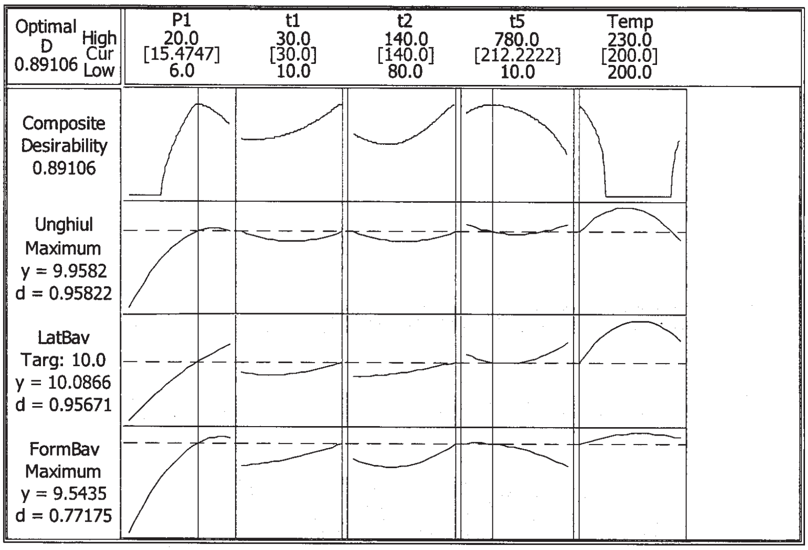
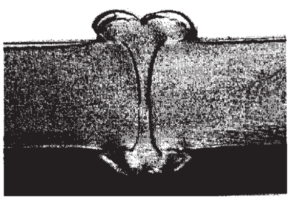


Fig. 10. Optimum technological version

Table 4
OPTIMUM WELDING PROCEDURE

Technological version	Value of D	Pressure P_1(MPa)	Time t_1(s)	Time t_2(s)	Time t_5(s)	Temperature T (°C)
Optimum PE 100	0.89	1.55	30	140	212	200

Table 5
EXPERIMENTAL RESULTS - OPTIMUM TECHNOLOGICAL VERSION

PROBE mark - macroscopically analyzed sample	c_{ef} (mm)	b (mm)	Imperfections according to CR 7/3	R_m (N/mm²)	α (°)
 Optimum PE 100	0.8	11.0	Not noticed	22.75	160

c_{ef} – minimum width of the weld; **b** – width of exterior burr;
R_m – fracture resistance; **α** – bending angle on the mandrel.

The optimization method consists in:

-obtaining an individual wanted value for each answer, (d=1, represents complete optimum);

-combination of wanted individual values to obtain a wanted compound value D (D=1, represents complete optimum);

-identification of optimum values for welding parameters.

In the case of the analyzed central-compound experiment, the graphical representation of optimization is illustrated in figure 10 (D= 0.89).

Optimum values of the welding parameters meeting all requirements imposed to objective functions are presented in table 4.

Table 5 presents results obtained from tests performed on a welded joint using the optimum technological version.

In this case using the welding parameters of the optimum version, a resistance at the level of that in the base material has been obtained. Sizes and shapes corresponding to interior and exterior burrs have been obtained, too.

Conclusions

The optimization of welding processes represents an especially important factor for the quality increase of welded joints and lifetime service of polyethylene pipelines.

An alternative of the classical mode to optimize industrial processes is represented by the planning of experiments assisted by computer. The planning programs and statistic calculus are useful elements by which can be considerably diminished the volume of work and costs necessary to optimize welding processes specific to polyethylene pipes.

Planning of experiments and statistic processing of results using non-linear experiments named Response Surface Design (RSD), lead to the establishment of mathematical relations regarding the dependence between objective functions, influence factors and their interactions.

The experimental results obtained within the work, on a number of 32 process versions led to the establishment of an optimum butt welding procedure using a heated tool for the analyzed polyethylene pipes PE 100.

Verifications performed on welding probes by the optimum technological version (D = 0,89), and the parameters: heating pressure P_1 = 1,55 MPa, heating time t_1 = 30s, maintaining time t_2 = 140s, welding time t_5 = 212s and temperature of the heated elements T = 200 °C, led to corresponding results.

References

1. DI LUCCHIO, R., LEONE, G., SANFILIPPO, G., Rivista Italiana della Saldatura, nr. 5, 2000, p.581
2. LEONE, G., Rivista Italiana della Saldatura, nr. 4, 2003, p.479
3. COCARD, M., Sudura ASR, nr. 2, 2001, p. 49
4. COCARD, M., CÂNEPARU, A., IACOB, M., International Conference - Structural Integrity of Welded Structures, Timişoara, 20 -21.11.2007, p.255
5. PUPĂZESCU, A.,Mat. Plast., **44**, no. 2, 2007, p. 130
6. KRISHNASWAMY, R.K., LAMBORN, J.M.,SUKHADIA, A.M., REGISTER, D.F., MAEGER, P.L., LEEVERS, P.S., Polym. Eng. Sci., **46,** nr.10, 2006, p. 1358
7. PUSCA, S., PAUN, M.A., TOMA, C., Mat. Plast., **44**, no. 1, 2007, p. 39
8. MITELEA, I., VARZARU, N., BORDEASU, I., POPESCU, M., Mat. Plast., **46,** no 1, 2009, p. 101
9. CICALĂ, E.F., Metode pe prelucrare statistică a datelor experimentale, Editura Politehnica, Timişoara, 1999
10. MIRON, M., GROZAV, I., TODEA, C., Noţiuni fundamentale de metodologie a cercetării ştiinţifice medicale, Editura Marineasa, Timişoara, 2004
11. PARK, J., LIDDY, J., Doc. IIW-XVI-764-00
12.PARK, J., LIDDY, J., Doc. IIW-XVI-765-00
13. COCARD, M.,BID ISIM nr. 2, 2004, p. 15
14. COCARD, M., GROZAV, I., Sudura ASR, nr. 5, 2005, p. 5
15. COCARD, M., GROZAV, I., IACOB, M., International Conference – Innovative Technologies for Joining Advanced Materials, Timişoara, 12-13.06.2008, p. 105
16. CICALĂ, E.F., Metoda experimentelor factoriale: proiectarea experimentelor, modelare, optimizare, Editura Politehnica, Timişoara, 2005
17.DEUTSCHER VERBAND für SCHWEISSEN und verwandte VERFAHREN e.V., Taschenbuch DVS-Merkblatter und –Richtlinien Fügen von Kunststoffen, Düsseldorf, 2006, p. 12-26; 212
18.CHEN, K., ZHOU, N., LIU, B., WEN, S., Polym. Int., **58,** nr. 2, 2009, p.117
19. KWON, H.J., JAR, P.Y., Polym. Eng. Sci., **46,** nr.2, 2007, p.1428
20. KIASS, N., KHELIF, R., BOULANOUAR, L., CHAOUI, K., Appl. Polym. Sci., **97,** nr.1, 2005, p.272
21. RAVI, S., TAKAHASHI, K., Polym. Eng. Sci.,, **42,** nr.11, 2002, p. 2146
22. KOICHI, K., Polym. Eng. Sci., **37,** nr.5, 1997, p. 777
23. COCARD, M., The1st South-East European Welding Congress– Welding and joining technologies for a sustainable development and environment, Timişoara, 24-26 mai 2006, p. 225
24. ILIESCU, S., GROZAV, I., PLESU, N., PASCARIU A., ILIA G., Polymer Engineering Science, Volume **48**, Issue 7, July 2008, Pages: 1304
25. MITELEA, I., VARZARU, N., BORDEASU, I., SCURTU, D., Mat. Plast., **46**, no. 4, 2009, p. 439

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