RESIDUAL STRESSES INDUCED BY PEEN FORMING PROCESSES APPLIED TO CONFORM ALUMINUM ALLOY PLATES

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Abstract. *The strong competition among aeronautical industries to enhance the capacity/weight ratio of the airplanes has fostered the research of new manufacturing technologies. Shot peen forming, a dieless forming process, is one of the most successful methods to produce slight and smooth curvatures on large panel shapes. Through the application of a regulated blast of small round steel shot on the work piece surface, a thin internal layer of residual compressive stress causes the elastic stretching of the upper surface, giving rise to a permanent non-plastic deformation of the whole piece. Considering that the equilibrium of the reactive efforts due to residual stresses generated by the shot impact on the surface plate is the mechanical phenomenon that explains its shape change, a series of systematic experiments have been carried out, in order to identify a functional model relating the controllable variables (shot diameter, blast pressure, coverage, preloading, thickness and mechanical properties of the work piece) with the residual stress distribution. Finally, proper statistical methods have been applied to the experimental data in order to obtain a preliminary peen forming process planning model based on the identified correlations between the controllable and observable variables of the process.*

Keywords: *peen forming, residual stress, hole drilling method*

1. INTRODUCTION

Shot peen forming is a plastic cold work process of shaping a metallic sheet through the impact of a regulated blast of small round steel shot on its surface, in order to impose to it a previously desired curvature. The succession of shots stretches the targeted surface, giving rise to a thin residual stress sub-layer, which, in turn, causes the piece to be overall elastically deformed.

Although shot peen forming formability could be evaluated by the *Almen* intensity — curvature measure of a standard steel strip submitted to a standard shot peening process (Almen and Black, 1963) — there is not a simple relationship between this measure and the residual stress distribution generated by the process, since different residual stress profiles can give rise to the same curvature (Guagliano, 2001). However, Cammet (2001) suggests that the *Almen* intensity is correlated to the total energy of deformation applied to the work piece during the process, which depends on the residual stress distribution developed in the thin plastified deformed layer.

In spite of several attempts to establish a mathematical model relating the *Almen* intensity to the peen forming process parameters, correlations between that measure and the residual stresses introduced during the forming is a subject that remains under investigation. For that matter, several authors like, for instance, Tatton (1986), have emphasized the importance of adopting experimental methods to investigate the shot peen forming phenomenology. Moreover, Wang *et al*. (2006) stress that the key industrial problem concerning shot peen forming process planning is the development of a method to identify the optimal process parameters that are able to form the work piece according to a previously desired shape.

The opinion of the heading paper's authors is that measuring residual stress profiles of a series of peen formed work pieces, under *a priori* known conditions, is essential to uncover the relationships among the variables of the process. Consequently, this article focuses the statistical analysis of experimental residual stress profiles developed inside the plastified sub-layers of 446 work pieces of aluminum alloy (7050 and 7475) 400mm x 50mm sheets with thicknesses of 2 mm, 5 mm, 10 mm and 15 mm, subjected to regulated peen forming processes. These work pieces have been formed at the Metallurgical Laboratory of the IPT (Instituto de Pesquisas Tecnológicas do Estado de São Paulo), using a *CNC* shot peening machine and auxiliary measurement instruments that permitted to generate regulated processes encompassing variations on the following parameters (Fleury *et al*., 2008) (see Table 1): spherical shot granulometry (0.7 mm (SAE-S230) 1.3 mm (SAE-S550), and 3.2 mm (1/8”)), shot blast pressure (three levels – *low*, *medium* and *high* – properly adjusted according to the type of spherical shot used), coverage (two levels – *high* or *low*, properly set according to the type of spherical shot used) and elastic preloading state (two levels – *non-preloaded work piece* and *simply supported work piece loaded by a concentrated force at its midpoint in order to generate stresses that do not overcome 90% of the material yield stress*).

Table 1. Important parameters and characteristics of the peen forming process experiments.

Symbol	Nomenclature	Unit	Meaning
d	Shot diameter	mm	Average diameter of the approximately spherical shots.
p	Blast pressure	MPa	Air pressure, measured at the entrance of the Venturi's shot peen machine.
c	Coverage	%	The rate between the shot peened area and the area exposed to the shot blast.
e	Plate thickness	mm	Work piece thickness.
f	Deflection	mm	Maximum deflection measured at the center of the work piece.
t	Static load	kN	Concentrated static load applied in the midpoint of the work piece.
RS	Residual stress	MPa	Residual stress measured at an in-depth point of the work piece plastified sub-layer.
MRS	Maximum residual stress	MPa	Maximum measured compressive residual stress.
SRS	Superficial residual stress	MPa	Residual stress measured at a superficial point of the work piece.
MSD	Maximum stress depth	mm	Maximum stress depth.
SLD	Stress layer depth	mm	Depth of the compressive stress layer.
U	Energy of deformation	Nmm/mm^2	Energy spent by peen forming process to shape the work piece.

The present paper is organized in the following way. In section 2, the residual stress genesis due to peen forming is briefly explained. The blind hole technique, used to measure the residual stress profiles developed in the plastified thin sub-layers of the peen formed work pieces, is the subject of section 4. Sections 5 and 6 focus the experimental set up and the results obtained during the tests. Section 6 presents the final conclusions of this work.

2. RESIDUAL STRESSES CAUSED BY SHOT PEEN FORMING

On a peen formed plate there is a non-homogeneous state of compression across its thickness caused by the residual stresses introduced by the shots. This compressive state of stress combined with the elastic recovery due to surface stretching, warps the plate in order to restore its state of equilibrium. Therefore, the surface exposed to the shots assumes a convex permanent shape under the action of a compressive stress field (see Figure 1a). Furthermore, the fatigue limit of the material is increased, since the compressive stresses contribute either to closing cracks or blocking their growth.

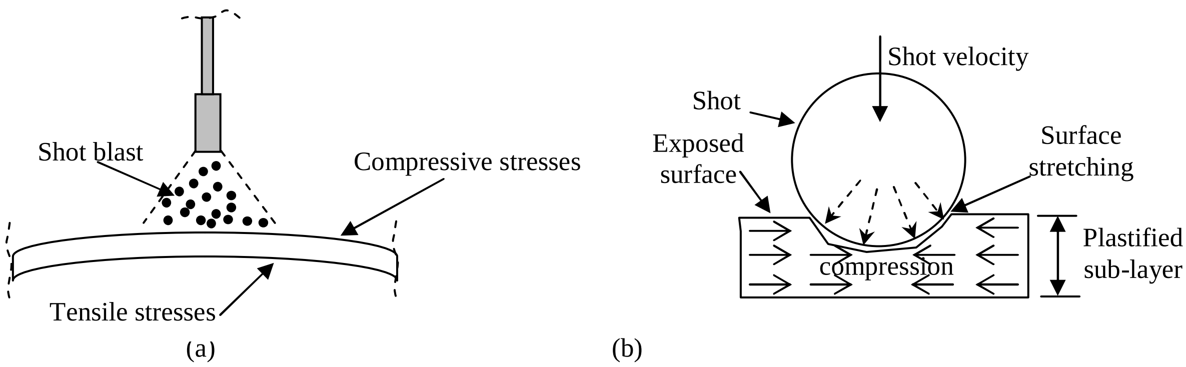

Figure 1. Plate subjected to peen forming.

If shot velocity direction were always normal to the plate surface (see Figure 1b), the plastic stretching of its fibers would be isotropic and, consequently, a hydrostatic state of stresses would emerge across the plastified sub-layer. As shot trajectories are random in nature, impacts coming from several directions would induce the stress tensor to assume an ellipsoidal shape. However, considering that a unique region of the plate may be subjected to several omni directional impacts during the process, it is reasonable to admit that only small differences shall be observed in the values of the principal stresses, unless plate aspect ratio is near 1 (i.e., width/length≈1), since in this case the effect of boundary conditions can accentuate the differences among the principal stresses.

So, as a first approximation, a hydrostatic compression state can be assumed for the residual stress distribution developed inside the plastified sub-layer of thin high aspect ratio plates subjected to peen forming. Thereby, focusing the shape of the residual stress profiles, the following behavior can be observed (see Figure 2): 1) compressive stress decreases across the depth until a minimum value — the saturation level, corresponding to the state in which compressive stress caused by the shots equalizes tensile stress due to the flexion of the plate elastic core — is attained; 2) at this point, stress gradient sign reverses and, consequently, stress starts to increase; 3) this process progresses until a tensile stress state is achieved.

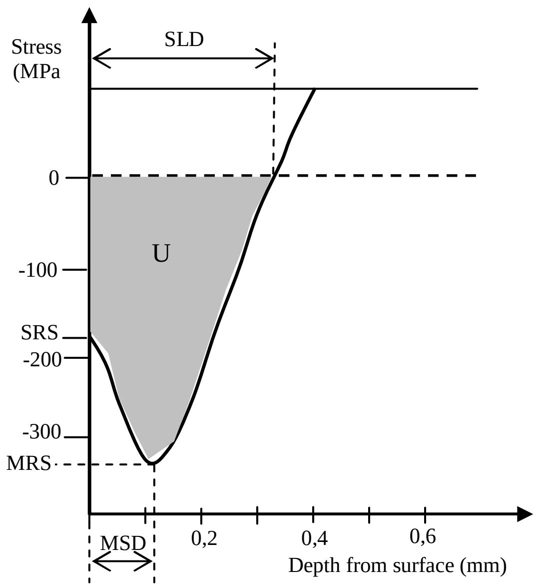

Figure 2.Typical profile of residual stresses due to peen forming.

3. THE BLIND HOLE TECHNIQUE FOR RESIDUAL STRESS DETERMINATION

The blind hole technique is currently one of the most popular for determining the residual stress distribution across the plastified sub-layer of a work piece.

Originally, this technique, described in ASTM E837 (ASTM, 2001) standard, was proposed to measure a field of uniform residual stresses. As indicated in the referred document, a small hole (1 to 5 mm diameter) must be made on the surface test material in order to produce stress redistribution (due to material removal) and subsequent local deformation. Then, the final relaxed deformation is measured using an electrical strain-gauge rosette bonded around the hole. Applying to the gauge measurements some coefficients indicated in that standard, the residual stresses are finally calculated.

The use of this method requires careful monitoring of the residual stresses magnitude, since stress concentration due to the notch insertion could cause local plastification at the hole root. Considering that for a uni-axial state of stress and small *D*/*w* ratios (where *D* refers to the hole diameter and *w* to the plate width) the stress-concentration factor is about three, some authors limit the use of the blind hole method to the measurement of residual stresses lower than $0.33\sigma_y$, where σ_y is the tested material local yield stress; in case of plane state stress, a maximum of $0.6\sigma_y$ is the accepted upper limit for residual stress measurements based on the blind hole technique.

It is important to explain why the yield stress considered above is the *local yield stress* and not the normally used *yield stress* of the material: the reason is that the high degree of cold work done by the peen forming to the plate material locally changes its mechanical properties, in particular its yield stress, which becomes greater than that which remains in the non-plastified core of the plate. Therefore, according to Nobre *et al*. (2006), depending on the cold work material sensitivity, the local yield stress can achieve a value significantly larger than that usually found in the materials handbooks.

As emphasized before, the original standard blind hole method only considered uniform residual stress fields. Therefore, many extensions to this method have been proposed in order to approach the cases where residual stress shows a non-uniform distribution. All the above referred proposals are variations of the so-called incremental hole technique (Soete, 1949), based on alternant incremental drilling and measurement operations – the first, to achieve the desired measurement depth, the second to measure the deformation at that depth. Using calibration factors generated by the application of the finite element method to the considered problem, the proper value of residual stress can be obtained at each depth.

Apart from the incremental hole drilling technique and its variations, several other methods to measuring non-uniform residual stress fields are related in the literature as, for instance, the Method of Average Strain Method (Nickola, 1986), the Method of Power Series (Schajer, 1981; Schajer, 1988) and the Integral Method (Flaman and Manning, 1985). This last one, indicated to approach strongly non-uniform residual stress fields, calculates residual stresses at each depth based on the contributions of the relaxed deformations measured along all the depths. Concerning resolution, that is the main weakness of all the mentioned techniques, Integral Method is the one that gives the best results; however, it must be emphasized that precision of the measurements generated by this method significantly decreases with the hole length.

4. EXPERIMENTAL APPARATUS AND TECHNIQUES

As mentioned in the first section of this article, a total of 446 aluminum alloy plates submitted to peen forming processes which *a priori* known characteristic parameters (shot diameter, blast pressure, coverage and pre-load), have been used in order to identify a cause-effect relationship among these parameters and the residual stress profiles developed in their plastified sub-layers. However, in this article, only the results concerning measurements of 42 (7075 alloy aluminum) specimens will be reported.

For measuring the residual stresses, it was applied the *H-Drill* program (Shajer, 2008), which implements the Integral Blind Hole Incremental Method mentioned before. The necessary high precision small holes have being machined with the aid of a high rotation drilling equipment - *RS-200*, supplied by Vishay Micro-Measurements Co. The strains were measured by the strain indicator equipment *P-3*, supplied by Vishay Micro-Measurements Co. Strain gauge rosettes used are the *PA-13-062RE-120*, supplied by Excel Sensores Ltda. Figure 2 shows the experimental apparatus.

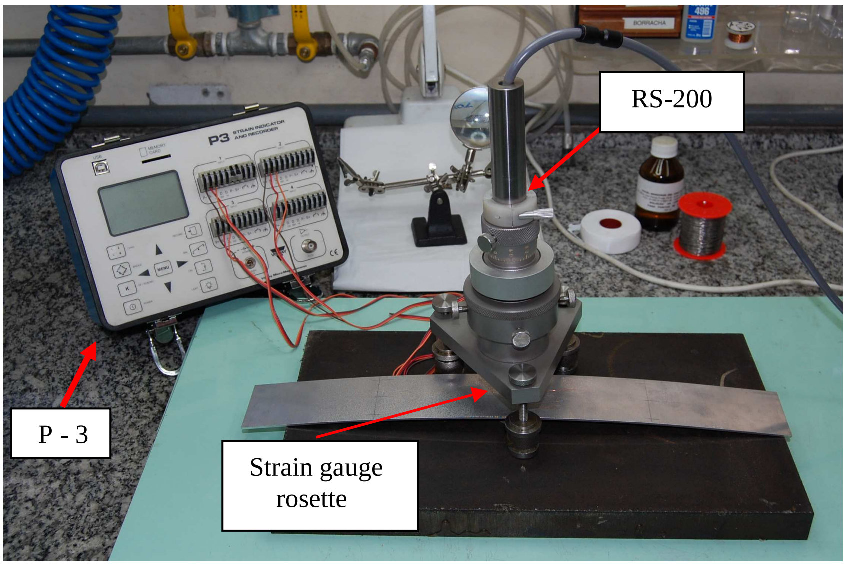

Figure 2. Experimental set up.

5. RESULTS AND ANALYSIS

Table 2 shows the list of parameters (*e*, *d*, *p*, *t*, *c*) considered in the experiments (see nomenclature in Table 1), their respective levels and the measurements of the dependent variables - maximum residual stress (*MRS*) and superficial residual stress (*SRS*). It is necessary to emphasize that the energy of deformation (*U*) (area under the residual stress profile graphics) has been considered in this analysis as an input variable.

Table 2. Experimental design relating work piece and peen forming process characteristic parameters to the characteristic values of the residual stress profile.

	e (mm)	d (mm)	p (MPa)	t (KN)	c (%)	TRS (MPa)	TRM (MPa)	U (Nmm/mm2)		e (mm)	d (mm)	p (MPa)	t (KN)	c (%)	TRS (MPa)	TRM (MPa)	U (Nmm/mm2)
1	2	0,6	0,138	37,5	200	-231	-442	111,2	21	10	3,2	0,138	42,2	200	-278	-734	138,4
2	2	0,6	0,276	37,5	85	-126	-277	62,5	22	10	3,2	0,138	422,0	60	-277	-749	190,6
3	2	0,6	0,276	37,5	200	-376	-572	127,6	23	10	3,2	0,138	422,0	200	-41	-568	167,6
4	2	0,6	0,276	375,0	85	-143	-402	106,0	24	10	3,2	0,172	42,2	60	-241	-282	48,1
5	2	0,6	0,276	375,0	200	-315	-489	145,5	25	10	3,2	0,172	42,2	200	-261	-954	257,6
6	2	0,6	0,414	375,0	92	-199	-626	164,4	26	10	3,2	0,172	422,0	60	-381	-506	148,2
7	5	0,6	0,276	42,2	85	-277	-511	178,2	27	10	3,2	0,172	422,0	200	-515	-939	321,7
8	5	0,6	0,276	422,0	200	-243	-327	100,6	28	10	1,4	0,138	42,2	60	-102	-899	307,2
9	5	0,6	0,414	422,0	92	-236	-563	163,0	29	10	1,4	0,138	42,2	200	-256	-441	127,9
10	5	0,6	0,414	422,0	200	-466	-480	87,5	30	10	1,4	0,138	422,0	200	-241	-369	77,0
11	5	1,4	0,069	42,2	60	-188	-256	90,0	31	10	1,4	0,207	42,2	60	-324	-725	241,4
12	5	1,4	0,069	42,2	200	-157	-455	127,6	32	10	1,4	0,207	42,2	200	-178	-638	240,5
13	5	1,4	0,069	422,0	60	-82	-367	113,9	33	10	1,4	0,207	422,0	60	-229	-383	138,7
14	5	1,4	0,069	422,0	200	2	-355	77,4	34	10	1,4	0,207	422,0	200	-228	-419	162,0
15	5	1,4	0,138	42,2	60	-176	-461	152,6	35	15	3,2	0,138	42,2	60	-149	-504	133,2
16	5	1,4	0,138	422,0	60	-84	-528	174,6	36	15	3,2	0,138	42,2	200	-65	-442	133,7
17	5	1,4	0,138	422,0	200	-281	-505	113,5	37	15	3,2	0,138	422,0	60	-197	-739	211,9
18	5	1,4	0,207	42,2	200	-361	-440	111,8	38	15	3,2	0,138	422,0	200	-383	-625	199,6
19	5	1,4	0,207	422,0	60	-137	-473	98,9	39	15	3,2	0,172	42,2	60	-153	-479	81,3
20	5	1,4	0,207	422,0	200	-128	-577	108,3	40	15	3,2	0,172	422,0	60	-271	-562	208,9

Aiming to derive an empirical function relating the maximum compressive residual stress (*MRS*) with the selected process variables and the energy of deformation, a planning analysis of the experimental data, with 5% significance level, has been carried out using multivariate regression implemented by the *Statistica* software (StatSoft, 2008).

Table 3 and Figure 3 show, respectively, the coefficients of the predictive variables of the proposed multivariate regression model and their correspondent Pareto diagram. In both table and figure it can be clearly noticed that the energy of deformation is the most significant variable of the process. Furthermore, there is not any variable that could be considered irrelevant; all the variables interact with the energy of deformation and all contribute to the residual stress prediction. Moreover, the high coefficients of correlation and their correspondent squared values 0.955 and 0.913 (Table 4) show a strong linear relationship between the dependent and independent variables.

Table 3. Mode coefficients model and predictors significance.

	TRM (param.)	TRM (t)	TRM (p)
Intercept	551,97	1,77785	0,092327
e	-47,84	-1,26470	0,222108
d	-98,11	-0,65950	0,517922
p	-1972,02	-1,61069	0,124643
t	-0,48	-1,42754	0,170545
c	-1,76	-1,84686	0,081274
U	-3,64	-2,26586	0,036027
e*d	5,96	0,99949	0,330805
e*p	113,82	1,05498	0,305390
d*p	142,82	0,26579	0,793420
e*t	0,00	0,06658	0,947649
d*t	0,06	0,39517	0,697363
p*t	0,41	0,36546	0,719028
e*c	0,15	1,50414	0,149890
d*c	-0,25	-0,58075	0,568608
p*c	1,98	0,56982	0,575842
t*c	0,00	0,54303	0,593769
e*U	0,07	0,65213	0,522558
d*U	-0,33	-0,93806	0,360633
p*U	3,90	0,77887	0,446177
t*U	0,00	1,14544	0,267030
c*U	0,00	0,48860	0,631021

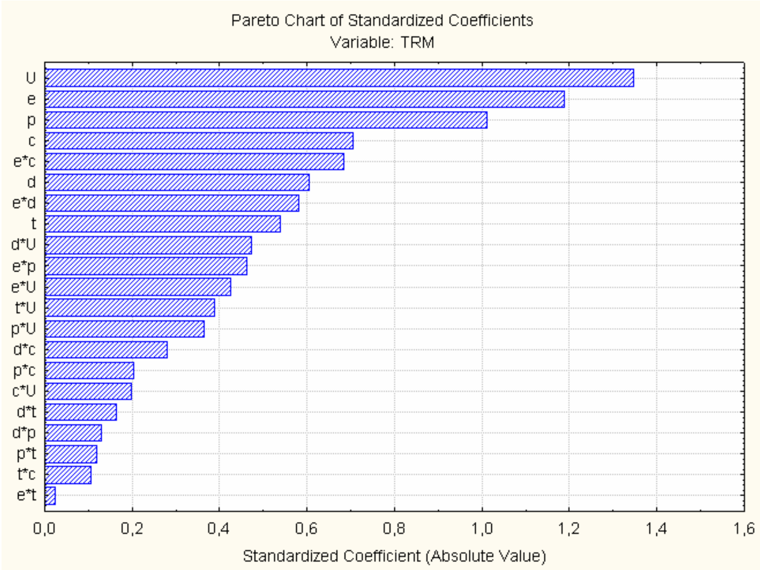

Figure 3. Pareto's diagram

Table 4. Model summaries.

Dependent variable	Test of *SS* Whole Model			
	Multiple *R*	Multiple R^2	F	p
MRS	0,955	0,913	8,981034	0,000009

In order to generate a mathematical model to predict optimum residual stress characteristics from the independent variables, the Desirability Optimization Method with multiple characteristics, proposed by Derringer and Suich (1980), has been applied to the experimental data. This method is based upon the so-called desirability function, that returns a value (*D*, the free desirability value) in the interval [0,1] according to the achieved objectives (Aggarwal *et al.*, 2008). Thereby, for instance: 0 indicates a value of the least desirable response; 1 indicates a value of the most desirable response; a value between 0 and 1 indicates the 'desirability' of the associated response.

Figures 4a-b show examples of desirability functions fitted, respectively, to the objectives of maximizing and minimizing the responses.

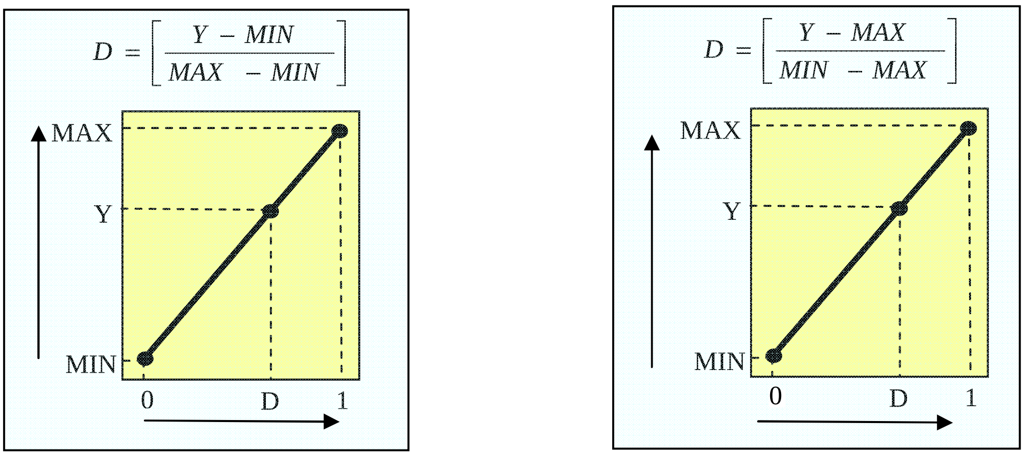

Figure 4. Desirability functions for: (a) response maximization; (b) response minimization.

In the problem focused below, *D*=1 means that the objective "obtain variable values that minimize the provided residual compression stresses (*MRS*)" has been achieved. As predicted values for the residual stresses vary in the range [-310 MPa, -960 MPa], the values 1, 0.5 and 0, for the desirability function, correspond, respectively, to -960 MPa, -635 MPa and -310 MPa.

Applying the *Desirability Tool* implemented by the *Statistica* software, a series of graphics relating the desirability function outputs of the primary independent pair of variables (*e*,*d*; *e*,*p*; *d*,*p*; *e*,*t*; *d*,*t*; *p*,*t*; *e*,*c*; *d*,*c*; *p*,*c*; *t*,*c*) have been generated. Figures 6 a-d show four of these graphics.

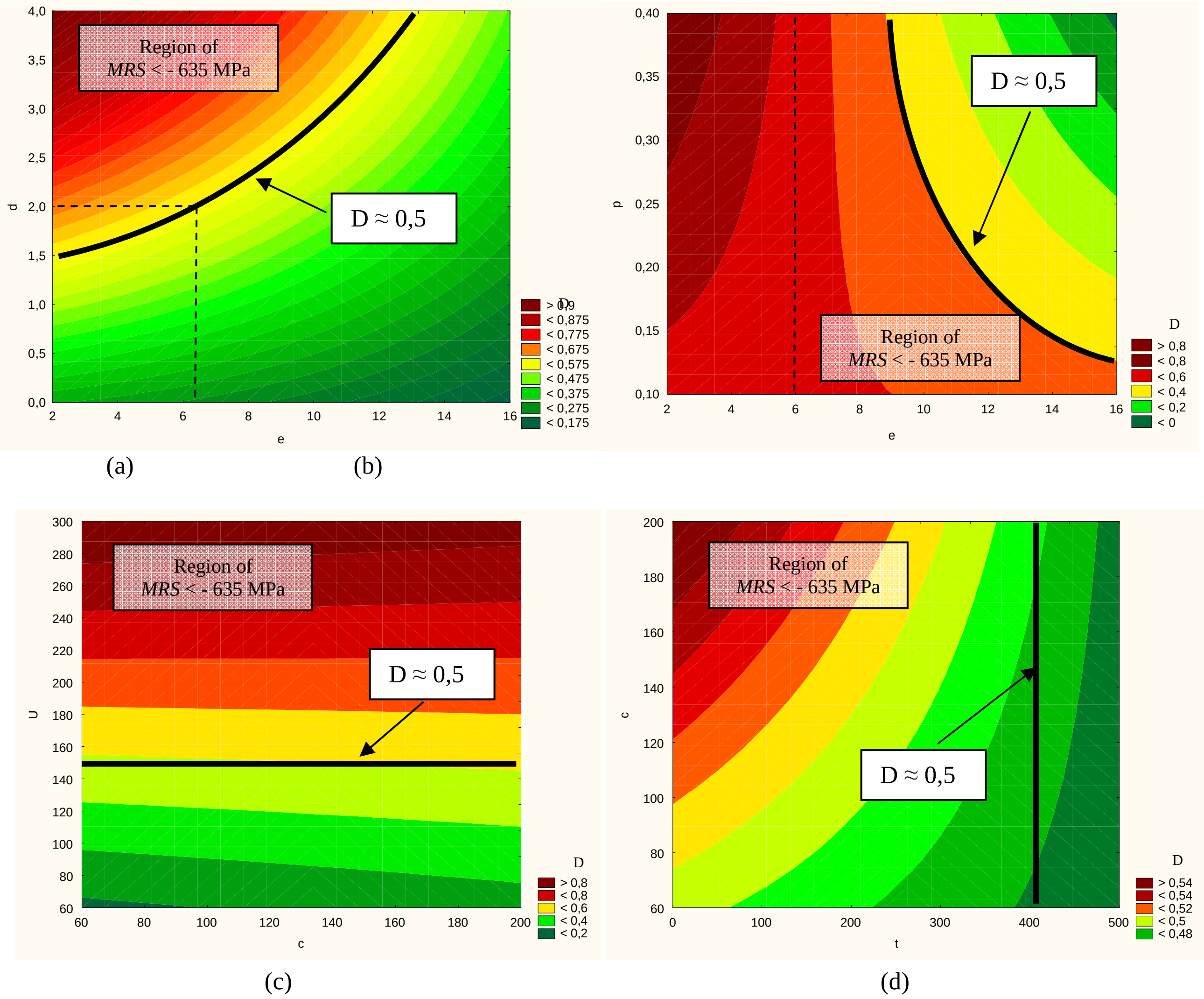

Figure 6: Contour plots for residual stress desirability function of the following primary independent pair of variables: (a) Plate thickness vs. Shot diameter; (b) Plate thickness vs. Blast pressure; (c) Coverage vs. Energy of deformation; (d) Static load vs. Coverage.

As a simple example of how to interpret the above graphics, we can notice that shot diameter (*d*) in the range of [1,5 mm, 4.0 mm] and deformation energy (*U*) greater than 150 Nmm/mm^2 lead to residual stresses below -635 MPa whatever be the values assumed by the other variables of the process. Moreover, graphics of the Figures 6a, 6b, 6c and 6d, respectively, show that: (1) if *e*=6,0mm and *d*=2,0mm, then *D*=0,5 and *MRS*=-635MPa; (2) if *e*=6,0mm, then *MRS*=-700MPa and *D*=0,6, whatever be the value of *p*; (3) for *U*>150Nmm/mm^2, then *MRS*>-635MPa and *D*>0.5, whatever be the value of *c*; (4) if t<422kN then *MRS*>-635MPa and *D*>0,5 whatever be the value of *c*.

The role of energy of deformation as an essential input variable of the mathematical model has been confirmed after comparing the results provided by a new factorial experimental analysis, using *Statistica* software, but excluding that variable from the set of input variables. The regression coefficients of this new generated model (R=0,809 e R^2=0.655) are lower than the ones generated by the previous model. However, it must be emphasized that: 1) considered as a process planning tool, this last generated model, not using energy of deformation as an input variable, can properly set up industrial peen forming processes in order to impose to a metallic sheet a previously established residual stress profile; 2) energy of deformation can be estimated using a Finite Element model, as described in Fleury *et al.* (2008), and so included as an input variable of the experimental model.

7. CONCLUSIONS

In this work, an experimental design has been proposed and carried out in order to identify an empirical based model relating the peen forming process variables and the characteristic parameters of the residual stress profiles developed in the sub-layers of a large set of aluminum alloy sheets subjected to that process. Applying the Desirability Optimization Method to the experimental data, a multivariate regression model has been finally synthesized and the following conclusions have been achieved: 1) there is a high linear correlation of the input predictor variables *thickness*, *shot diameter*, *blast pressure*, *preload*, *coverage* and *energy of deformation*, with the predicted variable *residual stress* (R = 0.955 and R^2 = 0.913); 2) if energy of deformation is not used in the model, its accuracy declines (new linear correlation of R = 0.809 and R^2 = 0.655); this should be attributed to the small size of the experimental set; 3) residual stress values below -635 MPa can be expected for any set of values of independent variables provided that the diameter of the shots be in the range [1,5 mm to 4,0 mm] and the energy of deformation be greater than 150 Nmm/mm^2; 4) the obtained mathematical model relating *thickness*, *shot diameter*, *blast pressure*, *preload* and *coverage* with the predicted variable *residual stress* (R=0,809 e R^2=0.655) can be used as a process planning tool to properly set up a peen forming process able to forming an aluminum alloy sheet exhibiting a previously defined residual stress profile.

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