Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Procedia CIRP 12 (2013) 163 – 168
www.elsevier.com/locate/procedia

8th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Optimization of the clinching tools by means of integrated FE modeling and artificial intelligence techniques

F. Lambiase*, A. Di Ilio

Dept. of Mechanical Energy and Management Engineering, University of L'Aquila, Monteluco di Roio, 67040 AQ, Italy
* Corresponding author. Tel.: +39 0862 434343; fax: +39-0862-434318 .E-mail address: francesco.lambiase@univaq.it.

Abstract

In the present work, an optimization of the clinching tools involving extensible dies is performed to increase the clinched joints strength. The clinched joint strength is influenced by the lock parameters, which in turn depend on the clinching tool geometry. A finite element model is developed to predict the effect of the clinching tool geometry on lock parameters and recursively optimize the tool geometry. In order to reduce the number of FE simulation runs, an artificial Neural Network (ANN) model is utilized to predict the behavior of clinched joints produced with a given clinching tools configuration. The ANN is trained and validated by using the results of the finite element model produced under different clinching tools configurations. Finally, an optimization tool based on a Genetic Algorithm tool was developed to demonstrate the effectiveness of the proposed approach.

Selection and peer review under responsibility of Professor Roberto Teti

Keywords: mechanichal fastening; joining; forming, clinching, metal sheet

1. Introduction

Clinching is a metalworking process by which two or more metal sheets are joined locally without the employment of additional elements such as screws, pegs, rivets, bolts and nuts, resulting in a reduction of the production cost and the run time [1]. In addition, mechanical clinching does not require a surface preparation such as competing technologies e.g. drilling (riveting), cleaning and roughening of the surface (adhesive boding) and other types of surface preparations (arc welding). This method is also suitable for those applications where a good corrosion resistance is required; because of such advantages and the flexibility of the process, clinching is utilized in a wide range of applications and can be applied to different materials such as low carbon steels, high strength steels [2], aluminium alloys [2], magnesium alloys [3] and even hybrid joints metal-metal and metal-polymer joints [4]. Clinch joints are frequently utilized in automotive sub-assemblies [5], building components [6] or steel cases. In order to guarantee the required strength of clinched joints, several characterization tests have been utilized, e.g. tensile tests on H-shaped samples, shear tests, fatigue tests [5] and also impact tests [7]. Basically, two different clinching schemes are available today, a TOX type, which uses a grooved fixed die and a TOG-L-LOC type (also known as Eckold method) involving an extensible die [8]. Several studies have been carried out on the TOX configuration involving numerical simulations based on finite element methods for analyzing the effects of the tools geometry on the joints strength [9]. Generally, both the clinching joint formation and the separation of sheets are simulated for such a purpose. The latest works on the subject have been focused on the optimization of the clinching tools geometry for the increase of the joint strength. An optimization method of the clinching tools using moving a least-square approach is introduced in [10], while an inverse approach for the identification of the clinching tools geometry is proposed in [7]. Although these methods have demonstrated to be able to determine the optimal geometry of the clinching tools within a reasonable number of iterations, they have been mainly applied for the optimization of the clinching tools for a restricted couple of sheets. By contrast, the em-

2212-8271
Selection and peer review under responsibility of Professor Roberto Teti
doi:10.1016/j.procir.2013.09.029

ployment of extensible dies permits to join a series of sheets having a wide range of thicknesses with a single set of clinching tools, since the die, which is composed of two or more sectors can spread radially. Thus, an optimization of the clinching tools for a range of sheets thicknesses would be more beneficial in several fields, such as the assembly of steel cases and components used in civil applications, where a frequent change of the clinching tools would severely increase the run time.

In this study, a numerical model of the clinching joint formation using an extensible die is developed by a finite element method and the influence of the process parameters is analyzed through the employment of design of experiments and a statistic approach. The FE model involves the simulation of both the clinch joint formation and the characterization of the joint. A design of experiments approach is involved to highlight the effect of the process parameters, i.e. the tools geometry and the sheets thickness on joint profile. Attention was paid to the main clinch geometrical characteristics that are the neck thickness and the undercut. Thus, the optimal configuration of the clinching joint was found by developing a flexible expert system based on an artificial Neural Network and a Genetic Algorithm.

2. Methodology

The first part of the proposed method involves the development and the validation of a finite element model and by simulating the clinching process under different processing conditions. To this end, a design of experiments approach, based on a Taguchi's orthogonal array, was involved to reduce the number of simulations. The second part of the proposed methodology is based on the development, the training and the validation of an artificial Neural Network (ANN) model in which the predictions of the FE simulations are used as the training and the validation data sets. The ANN is utilized to interact with an optimization tool (OT) rather than a direct connection between the FE modeling and the OT, as well as in [10], for two reasons: (1) the simulation time is significantly longer than the optimization tasks, thus its implementation within the optimization procedure would represent the bottleneck of the OT, and (2) the employment of the ANN allows to analyze several design solutions in fewer time. Indeed, after the network training and its validation, the network can be reused to analyze other design solutions and objective functions without requiring further FE runs.

A series of preliminary experimental tests were conducted using an extensible die configuration in order to calibrate and validate the FE model. The extensible dies (ED) are constituted by a fixed die anvil and a series of die sectors that can slip radially. Such radial motion is partially constrained by a rubber spring as depicted in Fig. 1. A Jurado clinching machine model Python is used to conduct the experimental tests. The geometrical characteristics of the clinching tools are: the punch diameter d = 4.0 mm; the die anvil diameter D = 5.0 mm; the die depth h = 1.1 mm. AISI 1010 sheets with nominal thickness of 1.0 mm were used in the experiment tests. The mechanical properties of the sheet material were determined by performing a series of tensile tests on sheet samples designed according to ASTM E08 M-04 for sheets characterization with a gauge length of 50 mm. The material characteristics are reported in Table 1.

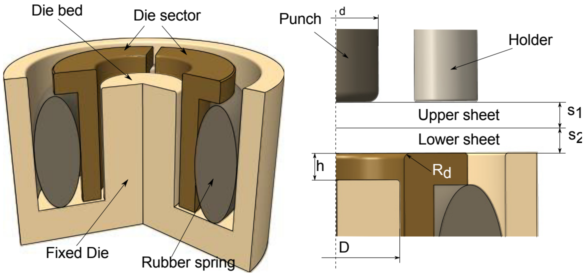


Fig. 1 Schematic representation of clinching tools with extensible die.

Table 1 Mechanical characteristics of AISI 1010.

Mechanical behavior	Value
Young Modulus [GPa]	210
Poisson's ratio	0.3
Ultimate tensile strength [MPa]	320
Initial yield stress, σ_0 [MPa]	88
Fitting function used in FE modelling with parameters obtained from stress-strain curves	$\sigma_{eq} = K\,\varepsilon^n$
K [MPa]	364
n	0.27

2.1 Design of Experiments

Design of experiments was adopted to define the simulation plan according to the involved process parameters. A L27 Taguchi's orthogonal array was utilized to investigate the effect of five design factors over three levels. Thus, the higher order interactions were neglected to reduce the number of the simulations trials. The parameters considered in the analysis were: the punch diameter (d), the wall clearance (D - d)/2, the die bed depth (h), the corner radius of the die sectors (Rd) and the sheets thickness, which was assumed to be equal for both sheets ($s = s_1 = s_2$). The remaining process conditions, that are the punch corner radius (0.2 mm) and the pressure on the holders (500 N) were kept constant among the simulations. Each parameter had three levels, as reported in Table 2, which were chosen to cover a relatively wide range of combinations.

Table 2 Geometrical parameters and levels.

Factors	Level 1	Level 2	Level 3
Punch Diameter, d [mm]	3.0	4.0	5.0
Clearance, (D-d)/2 [mm]	0.5	0.6	0.7
Sheet thickness, s [mm]	0.5	1.0	1.5
Die Depth, h [mm]	1.0	1.25	1.5
M, sector corner radius, R_d [mm]	0.2	0.3	0.4

2.2 *Numerical model*

A 3D finite element model was used to model the clinching process. An elastic-plastic material model with an isotropic material behavior was assumed. von Mises yielding model was adopted for the sheets, while the tools were simulated as rigid bodies. A penalty contact algorithm was assumed with a Coulomb friction with $\mu = 0.15$ for all the contacts. 8-node linear elements with reduced integration were adopted with different mesh densities depending on the amount of the localized deformation. The simulation consisted of two steps: first the clinching process was simulated; then, the tensile test was reproduced by constraining the lower sheet and loading the upper one vertically.

2.3 *Artificial Neural Network*

The ANN was trained to learn the nonlinear relationship between the design parameters and the joint characteristics, that are the lock parameters (the undercut and the neck thickness) and the joint strength. The basic ANN parameters e.g. the number of the hidden layers, the number of the neurons, and the transfer functions were determined by performing a series of preliminary trials. Various network configurations were examined ; finally, an ANN with one hidden layer (which obtained the best performances among the other analyzed solutions) was adopted for further investigation. The neural network architecture consisted of five input neurons (corresponding to the clinching tool design parameters), a hidden layer with 10 neurons and 3 output layers (corresponding to the 3 outputs to be predicted) with tag-sigmoid transfer functions. A feed forward back propagation algorithm was adopted to train the network within the Matlab framework. The training dataset was composed by all the 27 simulation results from the orthogonal array and two intermediate datasets were used for validation purposes.

3. Methodology

3.1. *Validation of numerical model*

The calibration and the validation of the FE model were performed by a comparison of the experimental measurements and the numerical predictions of the lock parameters, other than the joint strength. A satisfactory agreement between the numerical predictions and the experimental measurements was found; indeed, the maximum error in the evaluation of the neck thickness was 5% and that of the interlock was 7%. In addition, the same damage mechanism i.e. the button separation and the necking of the upper sheet [2] was found under all the analyzed conditions. After validating the FE model, the FE predictions were involved to train and validate the artificial Neural Network. Preliminary results are discussed under this section while the description of the expert system for the selection of the optimal clinching tool set is treated in the next section. Because of the parameters determining the clinched joint strength are the undercut (t_s) and the neck thickness (t_n), shown in Fig. 2, an analysis of the process parameters effect on lock parameters was conducted.

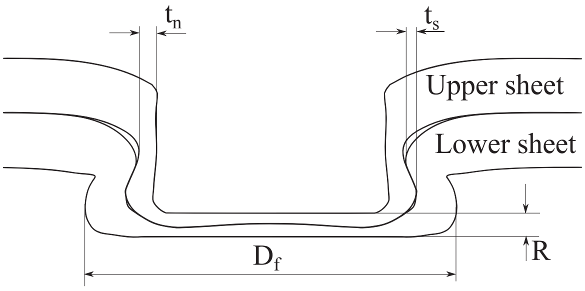


Fig. 2 Main lock parameters of a clinched joint.

Fig. 3 depicts the mean contribute of each parameter reported as the main effect plot of the neck thickness and the undercut. As can be observed, all the involved process parameters affect significantly the lock parameters since the slope of the plots is not negligible. In addition, all the analyzed process parameters (with the exception of the punch diameter) have opposite effects on the neck thickness and the undercut. The complex relationships among the process and the lock parameters make difficult to solve the optimization problem with a procedural approach.

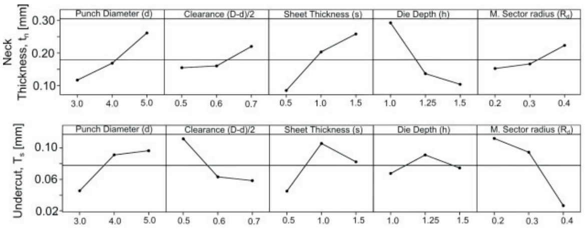


Fig. 3 Main effect plot for Neck thickness and Undercut.

An analysis of the process parameters influence on obtained the joint strength was also conducted. The main effect plots of clinched the joint strength is depicted in Fig. 4. The joint strength generally follows a monotonic trend with the process parameters with exception of the punch radius for which a peak is exhibited under the intermediate level. According to Fig. 4, the strength slightly decreases with the die clearance, the die depth and the fillet radius of the movable die, while it increases with the sheet thickness. Before presenting the optimization procedure of the process parameters, a brief discussion on their effect on the material flow is presented. As can be observed in Fig. 3, the increase of the punch radius would be beneficial for both the neck thickness and the undercut. This can be attributed to a major material flow within the cavity volume. In addition, an increased punch radius also involves a higher circumferential dimension of the joint that leads to a further increase of the joint strength. On the other hand, the increase of the punch radius comes with an increase of the required clinching load (which is proportional to the area of flat punch face). An increase of the die clearance causes a reduction of the undercut; therefore low values of die clearance should be preferred. Nevertheless, attention must be paid to avoid an excessive reduction of the neck thickness. Regarding the sheet thickness, thicker sheets were characterized by a thicker neck thickness; however, the effect on the undercut was much more complex. Indeed, an increase of the sheet thickness allows a better filling of the cavity volume; however the employment of sheets with excessive thickness causes an early displacement of movable sector leading to a smaller undercut. By contrast with conventional fixed dies, whereas an increase of the die depth induces an increase of the undercut, a different effect was exhibited when extensible dies were involved.

3.2. ANN prediction and validation

As above mentioned, all the 27 FE simulations were utilized to train and develop the ANN. Some interpolations of the FE results were performed on the intermediate input levels to enlarge the training data set. The comparison between the ANN predictions and the simulation results concerning the clinched joint strength are shown in Fig. 4. A clear agreement between the FE results and the ANN predictions is observable. Indeed, the effect of the process parameters are well captured by the ANN leading to an error smaller than 5%. On the other hand, some singularities were discovered for some predictions performed by the developed Neural Network whereas the error reached even the 15%.

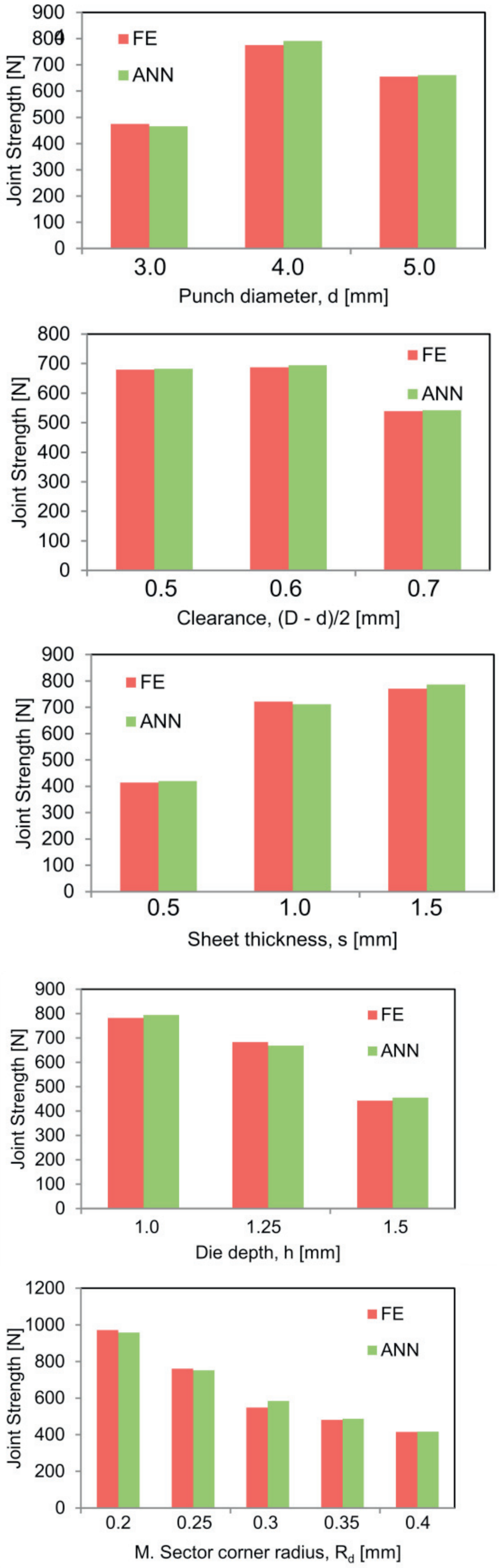


Fig. 4 Comparisons between main effects calculated by FE and ANN predictions.

4. Optimization of clinching tools with proposed expert system

The main objective of the present research is to develop a flexible system for the optimization of the clinching tools with respect to different objective functions. Regardless the target of the optimization, the proposed expert system is designed to determine the optimal clinching tools set producing the highest strength of the clinched joints. A genetic algorithm was thus developed to perform the optimization task. A chromosome length of 4 strings was adopted; each of the chromosome strings represented a design parameter i.e. punch diameter, clearance, sheet thickness, die depth and corner radius of the die sector. Each population is composed by 20 chromosomes. One point crossover was used for production of new populations and, in order to avoid local maxima, mutation (with a probability of 90%) was also involved. As above mentioned, different objective functions can be optimized; thus two cases were analysed to demonstrate the effectiveness and flexibility of the presented method: (case 1) optimal tool design for a given sheet thickness and (case 2) a tool selection for joining a range of sheet thicknesses.

4.1. Optimization of clinching tools for a given sheet thickness (Case 1)

The proposed model was tested for the optimization of a single thickness at a time. To this end, the objective function described in Eq. 1 was assumed.

$$f(d,D,h,R_{\mathrm{d}})| = -JointStrenght(d,D,h,R_{\mathrm{d}})\ |_{S=S^*} \qquad (1)$$

whereas s* is the actual thickness of the sheet for which the clinching tools have to be optimized. Thus, different values of s* were analyzed leading to different clinching tools configurations. The optimized design parameters calculated for the different s*-values are reported in Table 3. As expected, each sheet thickness would require a specified clinching tools set with the exception of Rd parameter which was set to the lower lever regardless the processing condition.

Table 3 Optimal configurations achieved with obj. function in eq. 1

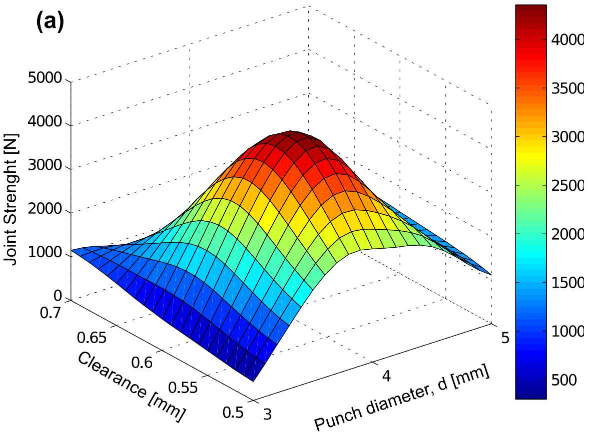
s*	d	D	h	R_d	Strength [kN]
0.5	3.9	5.1	1.3	0.2	4.39
1.0	4.2	5.4	1.3	0.2	3.65
1.5	4.5	5.5	1.3	0.2	3.28

4.2. Flexible optimization of clinching tools over a range of sheet thickness (case 2)

As previously demonstrated, each sheet thickness would require a different clinching tools set. Nevertheless, whether a multitude of thicknesses have to be joined, the frequent setup of clinching tools would be deleterious if the setup time is not masked. In addition, the adoption of different clinching tools sets for different thickness would be difficult to manage and relatively expensive. To this end, the determination of a clinching tool configuration which can lead to quality joints produced on different sheet thicknesses can be faced with the proposed optimization tool by using the objective function in Eq. 2.

$$f(d,D,h,R_{\mathrm{d}}) = -\sum JointStrenght(d,D,s_{\mathrm{i}},h,R_{\mathrm{d}}) \qquad (2)$$

Thus the optimization tool was utilized for joining sheets metal of equal thickness ranging from 0.5 + 0.5 mm, to 1.5 + 1.5 mm. The optimal configuration and strength predictions pertaining to the different values of s are reported in Table 4. As expected, the joints produced with the “flexible configuration” are generally slightly weaker than those produced with a thickness oriented optimization (Case 1), however such difference was not relevant for s* = 0.5 mm and s* = 1.5 mm, while for s* = 1.0 mm a reduction of almost the 15% was observed. Indeed, for s* = 1.0 mm, a steep decrease of the joint strength occurred as moving away from the maximum strength (occurring for d = 4.3 mm). Conversely, the joint strength for s* = 0.5 mm and s* = 1.5 mm exhibited a more gentile decrease of the strength as moving away from the optimal condition.



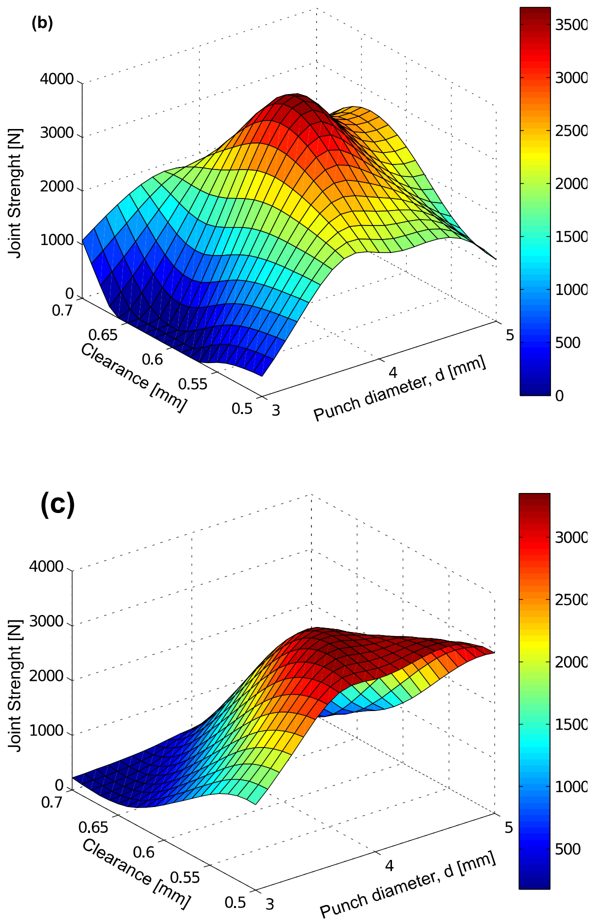


Fig. 5 Variation of joint strength with punch diameter and clearance with h = 1.3 mm, Rd = 0.2 mm for different sheet thicknesses (a) s = 0.5 mm (b) s = 1.0 mm and (c) s = 1.5 mm.

Table 4 Optimal die configurations achieved with obj. function in Eq. 2.

s*	d	D	h	R_d	Strength [kN]
0.5	4	5.2	1.3	0.2	4.35
1.0	4	5.2	1.3	0.2	3.11
1.5	4	5.2	1.3	0.2	3.27

Conclusions

The present study was aimed at developing a flexible tool for the optimization of the tool selection in the clinching process with extensible dies. The effect of the process parameters on the lock parameters and the joint strength was assessed by the FE simulations. An Artificial Neural Network was developed to predict the main characteristics of the clinched joints under different processing conditions. Finally an optimization tool, based on a genetic algorithm codification was developed for the optimal selection of clinching tools. Unlike previous studies, the optimization was performed to select a clinching tool configuration that allows gathering high strength joints over a series of sheet thicknesses. In addition, since the expert system was designed for reusability, different goals can be achieved by changing the objective function, without the need of running further simulations of the clinching process.

Acknowledgements

The authors would like to thank the support of Jurado Ldt of Rivotorto di Assisi (PG) (Italy) for supplying part of the experimental equipment utilized in the experiments.

References

[1] Varis, J., 2003. A simple testing-based procedure and simulation of the clinching process using finite element analysis for establishing clinching parameters, Thin-Walled Structures, 41, p. 691.
[2] Lee, C-J, Kim, J-Y, Lee, S-K, Ko, D-C, Kim, B-M, 2010. Parametric study on mechanical clinching process for joining aluminum alloy and high-strength steel sheets, Journal of Mechanical Science and Technology, 24, p. 123.
[3] Neugebauer, R., Kraus, C., Dietrich, S., 2008. Advances in mechanical joining of magnesium, CIRP Annals - Manufacturing Technology, 57, p. 283.
[4] Grujicic, M., Sellappan, V., Arakere, G., Seyr, N., Obieglo, A., Erdmann, M., et al, 2008. "The Potential of a Clinch-Lock Polymer Metal Hybrid Technology for Use in Load-Bearing Automotive Components," Journal of Materials Engineering and Performance, 18, p. 893.
[5] Carboni, M., Beretta, S., Monno, M., 2006. Fatigue behaviour of tensile-shear loaded clinched joints, Engineering Fracture Mechanics, 73, p. 178.
[6] Pedreschi, R., Sinha, B., 2008. An experimental study of cold formed steel trusses using mechanical clinching. Construction and Building Materials, 22, p. 921.
[7] Lee, C-J, Kim, J-Y, Lee, S-K, Ko, D-C, Kim, B-M, 2010. Design of mechanical clinching tools for joining of aluminium alloy sheets. Materials & Design, 31, p. 1854.
[8] Hamel, V., Roelandt, J.M., Gacel, J.N., Schmit, F., 2000. Finite element modeling of clinch forming with automatic remeshing. Computers and structures, 77, p. 185.
[9] Oudjene, M., Benayed, L., 2008. On the parametrical study of clinch joining of metallic sheets using the Taguchi method. Engineering Structures, 2008, 30, p.1782.
[10] Oudjene, M., Benayed, L., Delameziere, A., Batoz, J., 2009. Shape optimization of clinching tools using the response surface methodology with Moving Least-Square approximation, Journal of Materials Processing Technology, 209, p.289.