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Conference Title

Optimization of clinching tools by means of integrated FE modeling and Artificial Intelligence Techniques

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Abstract

In the present work, the design of clinching tools involving extensible dies is optimized to increase the clinched joint strength. The clinched joint strength is influenced by lock parameters, which in turn depend on the clinching tool geometry. Thus, it is necessary to predict the effect of clinching tool geometry on lock parameters for achieving stronger clinched joint. To this end, a finite element model was developed to predict the joint strength and to 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.

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

1. Introduction

Clinching is a metalworking process in which two or more metal sheets are joint locally without the employment of additional elements such as screws, pegs, rivets, bolts and nuts, resulting in reduction of costs and run time [1]. In addition, clinched joints do not require 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 applications where good corrosion resistance is required; because of such advantages and flexibility of the process, it 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 can be found in automotive [5], building [6] components or steel cases. In order to guarantee the strength of clinched joints, several characterization tests have been utilized, e.g. tensile test on H-shaped samples, shear tests, fatigue tests [5] and impact tests [7]. Basically, two different clinching schemes are available today, the TOX type, which uses a grooved fixed die and the TOG-L-LOC type (also known as Eckold method) involving an extensible die [8]. Several studies have been carried out on TOX configuration involving numerical simulations based on finite element methods for analysing the effects of tools geometry on clinch joint strength [9]. Generally, both the clinching joint formation and the separation of sheets are simulated to investigate the influence of clinching tools design parameters on obtained joint strength. The latest works on the subject have been focused on the optimization of clinching tools geometry in order to increase the joint strength. An optimization method of clinching tools using moving least-square approach is proposed in [10], while an inverse approach for determining the clinching tools geometry once given the goal strength is introduced in [7]. Although these methods have demonstrated to be able to determine the optimal geometry of clinching tools within a reasonable number of iterations, they have been mainly applied for optimization of clinching tools for a given couple of sheets. By contrast, the employment of extensible dies permits to join a wide range of sheet thicknesses with a single set of clinching tools, since the die (which is composed of three or more sectors) can spread radially. Thus, an optimization of clinching tools for a range of sheets thicknesses would be more beneficial in several fields, such as assembly of

steel cases and light components used in civil applications, where the frequent change of clinching tools would dramatically increase the run time.
In this study, a numerical model of clinching joint formation with extensible die is developed by finite element method and the influence of process parameters is analysed through the employment of design of experiments and statistic approach. The FE model involves the simulation of both clinch joint formation and testing to determine the clinch strength. Design of experiments approach is involved to highlight the effect of process parameters, i.e. tools geometry and sheets thickness on sheets profile inside the clinch joint. Particular attention was given to the main clinch geometrical characteristics such as neck thickness and undercut. Thus, the optimal configuration of clinching joint was found by developing a flexible expert system based on Genetic Algorithm approach.

2. Methodology

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

A series of preliminary experimental tests using an extensible die configuration were conducted in order to calibrate and validate the FE model. Extensible dies (ED) are mainly constituted by a fixed die bed and a series of die sectors which can spread radially. Such radial motion is partially constrained by employing a rubber spring as depicted in Fig. 1. A Jurado clinching machine model Python is used to perform the experimental clinch joints. The geometrical characteristics of the clinching tools are: punch radius d = 4.0 mm; minimum extensible die radius D = 5.0 mm; 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 sheet materials were determined by performing tensile tests on sheet samples designed according to ASTM E08 M-04 for sheet characterization having a gauge length of 50 mm. The material characteristics are reported in Table 1.

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

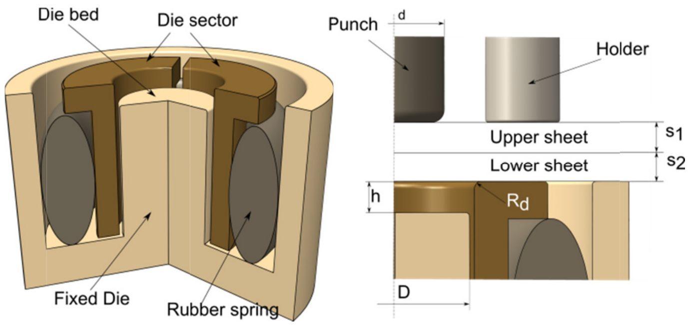

Fig. 1 Schematic representation of clinching tools with extensible die.

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, higher order interactions were neglected to reduce the number of 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 die sectors (R_d)and the sheets thickness, which was assumed to be always equal for both sheets ($s = s_1 = s_2$). The remaining process conditions, such as punch corner radius (0.2 mm) and pressure on holder (500 N) were kept constant in the simulations. Each parameter had three levels, as reported in Table 2, which were chosen to cover a 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 clinching process. An elastic-plastic material model with isotropic material properties was assumed. The von Mises yielding model was adopted for sheet material, while the tools were simulated as rigid bodies. A penalty contact algorithm was assumed with a Coulomb friction with μ = 0.15 for all contacts. 8-node linear elements with reduced integration were adopted with different mesh densities depending on the amount of localized deformation. The simulation was made of two steps: first the clinching process was simulated; then, the tensile test was performed by constraining the lower sheet and loading the upper one vertically to evaluate the joint strength.

2.3. Artificial Neural Network (ANN) modeling

An ANN was trained to learn the nonlinear relationship between design parameters of clinching tools and joint characteristics, i.e. lock parameters (undercut and neck thickness) and joint strength. The basic ANN parameters e.g. number of hidden layers, neurons, and transfer functions were determined by performing a series of preliminary trials. Various network configurations were examined including different number of hidden layers. 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 was represented by five input neurons (corresponding to the clinching tool design parameters), the 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 orthogonal array and two intermediate datasets were used for validation purposes.

3. Results and discussion

3.1. Validation of numerical model

The FE model calibration and validation were performed by a comparison of experimental measurements and numerical predictions of lock parameters (i.e. undercut and neck thickness), other than joint strength. A satisfactory agreement between numerical predictions and experimental measurements was found (e.g. the maximum error in the evaluation of neck thickness was 5 % and interlock 7 %). In addition the same damage mechanism i.e. button separation and necking [2], of clinched joint separation was found under all analysed conditions.

After validating the FE model with experimental results, the FE predictions were involved to train and validate the artificial Neural Network as well. Preliminary results are discussed under this section while the description of the expert system for optimal clinching tool selection is treated in 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 process parameters effect on lock parameters was conducted.

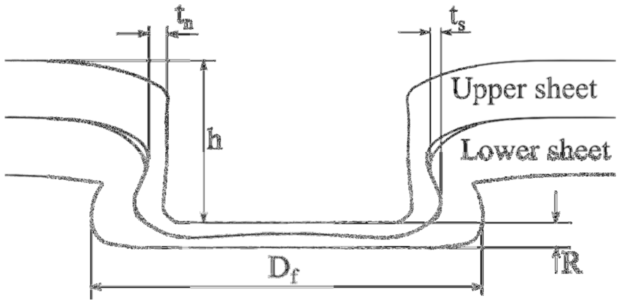

Fig. 2 Main lock parameters of a clinched joint.

Fig. 3 depicts the mean contribute of each parameter in terms of main effect plot of neck thickness and undercut. As can be observed, all the involved process parameters affect significantly the lock parameters, thus they are not negligible. In additions, all analysed process parameters (with the exception of punch diameter) have different effects on neck thickness and undercut. The complex relationships among process and lock parameters make difficult to solve the optimization problem by a procedural approach and justify the development of an expert system for optimization of clinching tools configuration.

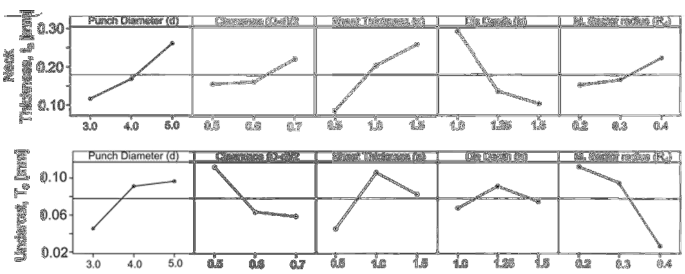

Fig. 3 Main effect plot for Neck thickness and Undercut

An analysis of process parameters influence on obtained joint strength was also conducted. The main effect plots of clinched joint strength is depicted in Fig. 4. The joint strength generally follows a monotonic trend with process parameters with exception of punch radius for which a peak is exhibited under the intermediate level. According to Fig. 4, the strength slightly decreases with clearance, die depth and fillet radius of movable die, while it increases with sheet thickness.

Before presenting the optimization of process parameters, a brief discussion on their effect on material flow is introduced. As can be observed in Fig. 3, the increase of punch radius would be beneficial for both the neck thickness and 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 joint strength. On the other hand, the increase of punch radius comes with an increase of required clinching load (which is proportional to the area of flat punch face). An increase of 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 neck thickness. Regarding the sheet thickness, thicker sheets were characterized by thicker neck thickness; however, the effect on undercut was much more complex. Indeed, an increase of sheet thickness allowed a better filling of cavity volume; however the employment of sheets with excessive thickness caused an early displacement of movable sector leading to a small undercut formation. By contrast with conventional fixed dies, whereas an increase of die depth induces an increase of the undercut, a different effect of die depth (h) on undercut 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 an ANN capable to predict the strength of clinched joints produced under different processing conditions. Some interpolations of FE results were performed on intermediate input levels to enlarge the training data set. The comparison between ANN predictions and simulation results concerning the clinched joint strength are shown in Fig. 4. A clear agreement between FE results and 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%.

4. Optimization of clinching tools with proposed expert system

The main objective of the present research is to develop a flexible system for optimization of clinching tools with respect to any given objective function. Regardless the target of the optimization, the proposed expert system is designed to determine the optimal clinching tools producing the highest strength of 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) tool selection for joining a range of sheet thicknesses.

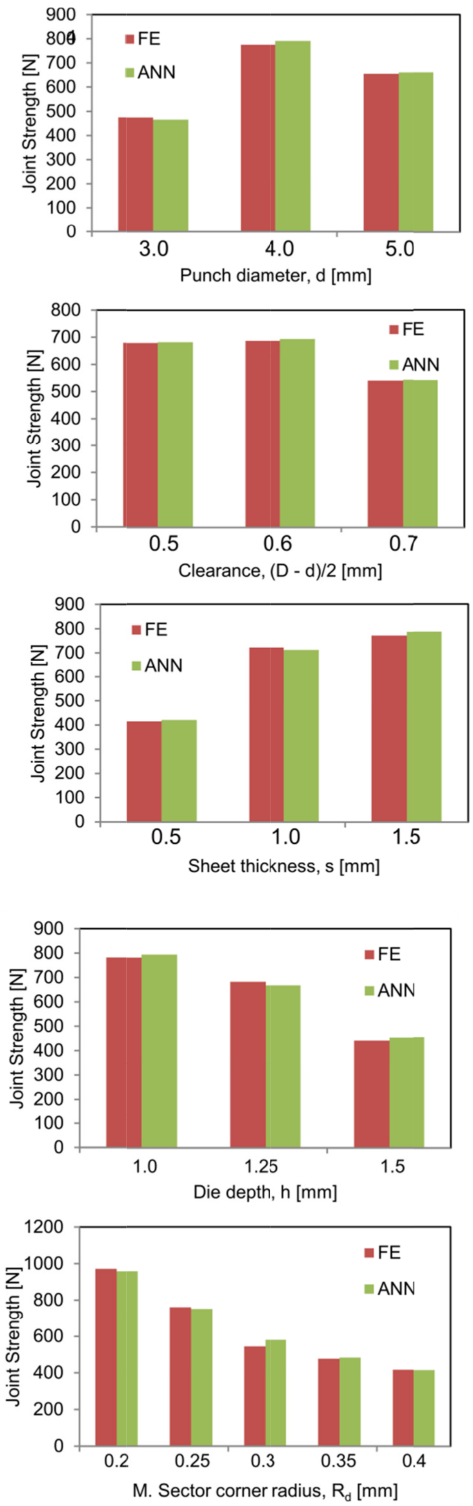

Fig. 4 Comparisons between main effects calculated by FE and ANN predictions.

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

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

$$f(d,D,h,R_d)|_{s=s*} \\ = -JointStrenght(d,D,h,R_d)\ |_{s=s*} \quad (1)$$

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 having different thickness would require different clinching tools with the exception of R_d 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 by clinching, 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.

$$f(d,D,h,R_d) \\ = -\sum_{i=1}^{n} JointStrenght(d,D,s_i,h,R_d) \quad (2)$$

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 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 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 strength as moving away from the better condition.

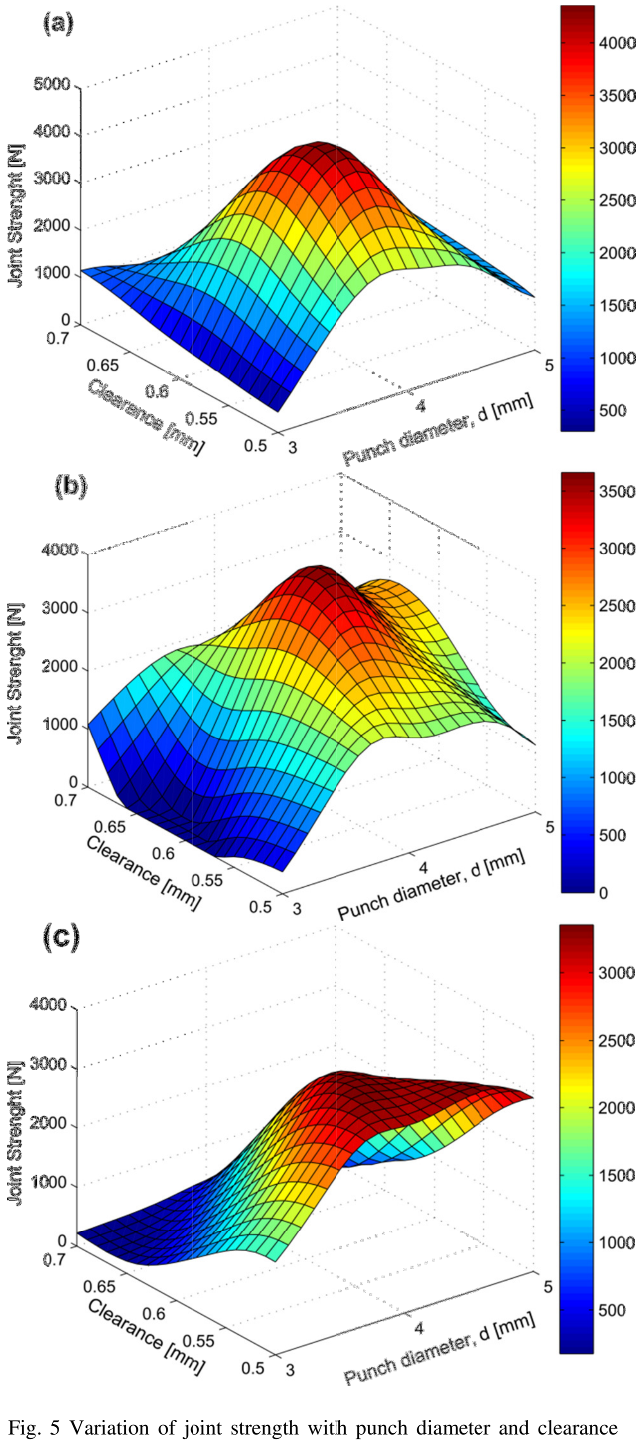

Fig. 5 Variation of joint strength with punch diameter and clearance with h = 1.3 mm, R_d = 0.2 mm for different sheet thicknesses (a) s = 0.5 mm (b) s = 1.0 mm and (c) s = 1.5 mm.

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 optimization of tool selection in clinching process with extensible dies. The effect of process parameters on lock parameters and joint strength was assessed by FE simulations. An Artificial Neural Network was developed to predict the main characteristics of clinched joints under different processing conditions. Finally an optimization tool, based on genetic algorithm codification was developed for optimal selection of clinching tools. Unlike previous studies, the optimization was performed to select a clinching tool configuration which allowed to gather 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 clinching process.

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