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The optimal design of sheet metal forming processes: application to the clinching of thin sheets

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Abstract: The production of high-strength clinched joints is the ultimate goal of the manufacturing industry. The determination of optimum tool shapes in the clinch forming process is needed to achieve the required high strength of clinched joints. The design of the tools (punch and die) is crucial since the strength of the clinched joints is closely related to the tools geometry. To increase the strength of clinched joints, an optimisation procedure using the response surface methodology, based on an adaptive moving target zone, is presented. The cost function studied here is defined in terms of the maximum value of the tensile force computed during the simulation of the sheets separation. Limitations on the geometrical parameters due to feasibility issues are also taken into account. The kriging interpolation is used to provide an approximation to the optimisation problem and to build the response surfaces.

Keywords: FEM; finite element method; clinching process; design of experiments; optimisation; RSM; response surface methodology; SQP algorithm; sheet metal forming; kriging interpolation.

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1 Introduction

The development of lightweight structures has greatly increased in the last decades and it constitutes the ultimate goal of the manufacturing industry, in particular the automotive industry. This tendency gives rise to economic, flexibility and environmental advantages. The lower the weight of an automobile body the lesser energy it uses and the lesser pollution it creates. In recent years, the development of some industrial mechanical joining techniques for thin sheets – such as self-pierce riveting, short pipe riveting and clinching, as alternative solutions to the traditional spot welding process (Barnes and Pashby, 2000a; Barnes and Pashby, 2000b) – has become increasingly important. On the other hand, contrary to the alternative joining methods above, spot welding is incompatible with lightweight material such as aluminium because of its high thermal conductivity and the natural surface oxide layer (Lee et al., 2010). However, despite the economic and flexibility advantages of the clinching process (Varis, 2006a), due to the fact that there are no additional joining parts, its strength can be lower than those obtained by other joining methods. Several authors have compared the strength of clinched joints and spot welded joints used in automotive industry (Varis and Lepisto, 2003; Mota and Costa, 2005) and have observed that there is a need to improve the clinched joints' strength to increase their application in the assembly of automotive components. The importance of studying in more depth the clinching process and moving towards the improvement of its mechanical performance has long been recognised. It is only in the last 30 years that the technology of clinching has significantly progressed (He, 2010). Extensive experimental and numerical studies have been carried out during the last two decades to study the basic mechanisms of the clinching process. Numerical studies, using the finite element method, and experimental tests are still ongoing today to provide a detailed database and knowledge with which the improvements in mechanical performance and quality of clinched joints can be achieved. For a comprehensive review of the clinching process, the reader is referred to He (2010). This review includes published work relating to finite element analysis of clinched joints, in terms of process, strength and vibration characteristics of joints.

As in many process and structural designs, the combination of numerical simulation using the finite element method with numerical optimisation techniques cannot be avoided. Achieving the optimal design of clinched joints is very time consuming, on top of material and manpower costs. When conducting experimental-based research, tests need to cover as many scenarios as possible, such as materials, geometries, loading and boundary conditions, etc. Therefore, the optimisation process is likely to be very expensive and highly time consuming (Pan et al., 1994; Lee et al., 2001). In contrast,

the development of numerical models using finite element analysis is a relatively quick and inexpensive process, especially in cases where there is access to supercomputer facilities. In such circumstances, only a very limited number of experimental studies are required for optimisation of joint systems. Numerical simulations should be capable of identifying the influence on the behaviour of the clinched joints of materials properties, geometries, friction, etc. As a result, the identification of optimum joint systems can be carried out efficiently and cost-effectively. If the optimisation process can be achieved through numerical simulation, the time period for developing a new joint system with high quality and required strength will be significantly shortened.

It is well known that the strength of clinched joints is influenced by process parameters (tool geometry, applied loads, etc.) as well as joint characteristics (sheet thickness, behaviour of materials, friction, etc.) (Varis, 2002; Hamel et al., 2000; Varis, 2003; Varis, 2006b; de Paula et al., 2007). Recently, Mucha (2010) has employed numerical simulation, for a better understanding of clinching process, in addition to experimental studies using round die, where the clinching joint was studied in terms of its characteristics and performances.

In this study, we limit ourselves to the influence of the clinching tool geometry (punch and die) on the strength of joints – as documented in Varis and Lepisto (2003), de Paula et al. (2007), Oudjene and Ben-Ayed (2008), and Oudjene et al. (2009) – where it has been clearly demonstrated that clinched joints with low strength can be modified and enhanced by various combinations of tool geometry.

Response Surface Methodology (RSM) is an efficient and widely established method for optimisation problems and it has various applications in the field of sheet metal forming processes. For the Y-shaped tube hydroforming process, Lorenzo et al. (2010) developed a successive two-optimisation procedure. First, a steepest descent method to reach an initial optimal solution is used. In the latter step of the optimisation, a response surface method is used in order to reach an optimal solution which is more satisfactory and in close proximity to the real optimum.

When applying RSM to a particular problem, two important issues have to be considered: the choice of the Design of Experiments (DoE) and the construction of accurate function approximations (Breitkopf et al., 2005; Lebaal et al., 2005; Naceur et al., 2006; Naceur et al., 2008; Lebaal et al., 2009a). The ultimate goal of this study is to develop a numerical optimisation strategy to obtain optimised clinching tool geometry leading to a greater strength of joints than that previously achieved (Oudjene et al., 2009).

In this work, it is proposed to combine RSM with FE-simulation using ABAQUS finite element code, in order to increase the tensile strength of clinched joints. The RSM is

coupled with an adaptive moving target zone, and using the central composite DoE (Oudjene and Ben-Ayed, 2008) with three levels for function evaluation. The kriging technique (Kaymaz, 2004; Li et al., 2005; Lebaal et al., 2009b) is also used in this work to build the response surfaces.

2 The optimisation procedure

2.1 Formulation of the optimisation problem

To increase the clinched joints' strength, the optimisation problem is expressed as follows:

$$\begin{cases} \max (J(X)) \\ \text{Subject to } x^u \leq x \leq x^v \end{cases} \quad (1)$$

where $J(X)$ is the objective function, x^u and x^v are the lower and the upper bound vectors of the design variable x , respectively.

The optimisation problem is to determine the geometry of punch and die, to achieve the required high clinched joints' strength; this corresponds to the maximum value of the cost function (J). The cost function (J) is related to the maximum tensile force F_T , obtained by loading the clinched joint vertically, and can be expressed under its normalised form as follows:

$$J = \frac{F_T}{F_T^0} \quad (2)$$

where F_T^0 represents the maximum tensile force for the non-optimised joint (with initial tool geometry).

The effects of all geometrical parameters displayed in Figure 3 have been studied in detail in Oudjene and Ben-Ayed (2008). Based on the average effect of parameters, only the parameters D (die diameter), B (die groove width) and G (punch radius) are considered as really influential parameters, thus the design variables x .

In the present study, only feasibility limitations are considered. Thus, the design variables (equation 3) are linked and are expressed as follows:

$$(X) : \begin{cases} X_1^u \leq X_1 = B \leq X_1^v \\ X_2^u \leq X_2 = D \leq X_2^v \\ X_3^u \leq X_3 = G \leq X_3^v \end{cases} \quad (3)$$

The objective function (equation 2) is implicit compared to the optimisation parameters, and its evaluation requires a large computation time. To find the optimum parameters with low cost and with a good accuracy, RSM is adopted using the kriging interpolation and coupled with a strategy of updating the search space.

2.2 Kriging interpolation

The kriging (Li et al., 2005; Lebaal et al., 2009a) interpolation method has proved to be a very powerful interpolation technique and it makes it possible to represent complicated functions. This method is applied in this work to represent the response surface in an explicit form,

according to design variables. The approximate relationship of the cost function can be expressed as follows:

$$\tilde{J}(X) = P^T(X)\beta + r^T(X)\alpha \quad (4)$$

$\beta = [\beta_1, \dots, \beta_m]^T$ is the coefficient vector and the random fluctuation, $r^T(X)\alpha$ is an interpolation of the residuals of the regression model, $P^T(X)\beta$ is used to represent the deviation of the global model so that the whole model interpolates response data from the function.

where

$$r^T(X) = \{M(X, X_1), \dots, M(X, X_{n1})\} \quad (5)$$

Then the unknown parameters α and β can be estimated as follows:

$$\alpha = M^{-1}(J - P\beta) \quad (6)$$

$$\beta = (P^T M^{-1} P)^{-1} P^T M^{-1} J \quad (7)$$

where

$$M = \begin{bmatrix} M(x_1, x_1) & \dots & M(x_1, x_n) \\ \vdots & \ddots & \vdots \\ M(x_n, x_1) & \dots & M(x_n, x_{n1}) \end{bmatrix} + \begin{bmatrix} \omega(x-x_1) & 0 & \dots & 0 \\ 0 & \omega(x-x_2) & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & \omega(x-x_n) \end{bmatrix} \quad (8)$$

The correlation function is defined in 3D as follows:

$$M_{ij} = \left(|x_i - x_j| \right) \quad (9)$$

A weight function of Gaussian type with a circular support (Lebaal et al., 2005) is adopted for the kriging interpolation:

$$\omega_i(x) = \begin{cases} 1 - \frac{e^{-(d_i/c)^2} - e^{-(r_w/c)^2}}{1 - e^{-(r_w/c)^2}} & \text{if } d_i \leq r_w \\ 1 & \text{else } d_i \geq r_w \end{cases} \quad (10)$$

This function is positive and its value decreases with the distance, $\|x - x_i\|$, and takes zero value outside the influence domain d .

where $d_i = \sqrt{\sum_{j=1}^n (x^j - x_{(i)}^j)^2}$ is the distance from a

discrete node x_i to a sampling point x in the domain of support with radius r_w , and c is the dilation parameter (for the computation, c was assumed to be equal to $r_w/4$).

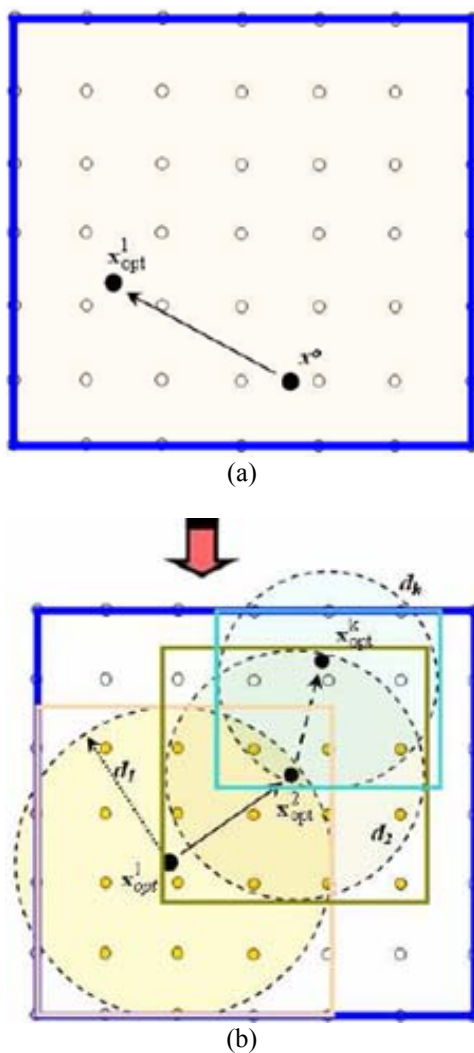
2.3 The optimisation strategies

The goal of RSM is to decrease the cost of functions evaluation in structural optimisation. The strategies adopted in this work allow precise approximations to build in order to find an

accurate global optimum. In this paper, we limit ourselves to a short presentation of the optimisation strategies which have the main advantage of avoiding a local optimum.

The kriging interpolation is not quadratic therefore it is probable that the Sequential Quadratic Programming (SQP) algorithm converges to a local optimum. First, a global approximation is made by considering a weight function which is equal to zero (a global approximation). In order to avoid a local optimum, successive optimisations are performed automatically using the SQP algorithm to obtain the best optimal solution starting from each point of the DoE. The best solution among those obtained from various optimisations is then considered (Figure 1a). After that, successive local approximations are built in the vicinity of the optima (Figure 1b) to obtain a more accurate approximation of the optimisation problem locally (centred around the best minimum). The iterative procedure stops when the successive optima of the approximate function become close. Finally, a finite element simulation is carried out to obtain the real tensile strength.

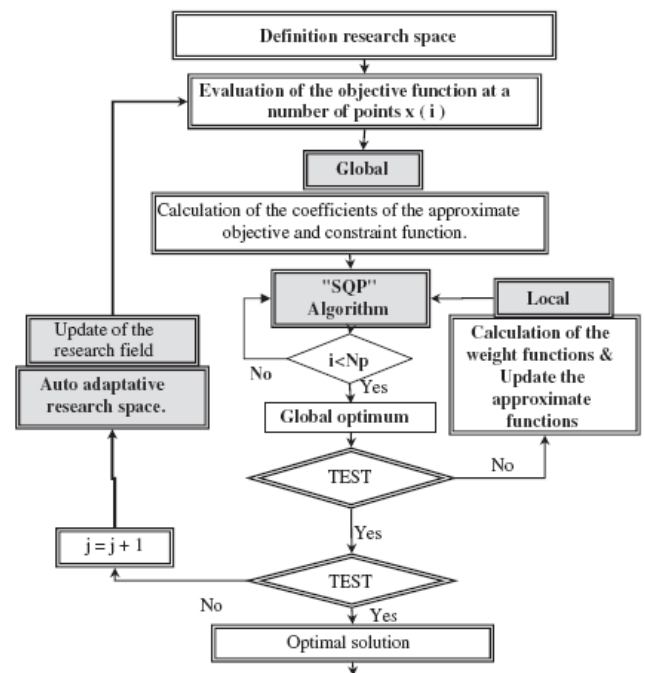
Figure 1 Progression of the optimisation procedure for 2D case: (a) global and (b) successive local approximations (see online version for colours)



During the progression of the optimisation procedure, the target zone moves and zooms on each optimum by reducing the search space by 1/3. In addition, evaluation points which have been already calculated are duly taken into account when working on a new search space. The optimisation procedure is stopped when the size of the search space becomes too small or when the successive optima become close together.

A Python Script is used to create the ABAQUS finite element model, to run the computations and to post-process the results, which are exported in an ASCII file. That file is then read by a FORTRAN programme, in which the response surface approximations and SQP algorithm are implemented. The general overview of the above procedure is shown in Figure 2.

Figure 2 The flowchart of the automatic optimisation strategy



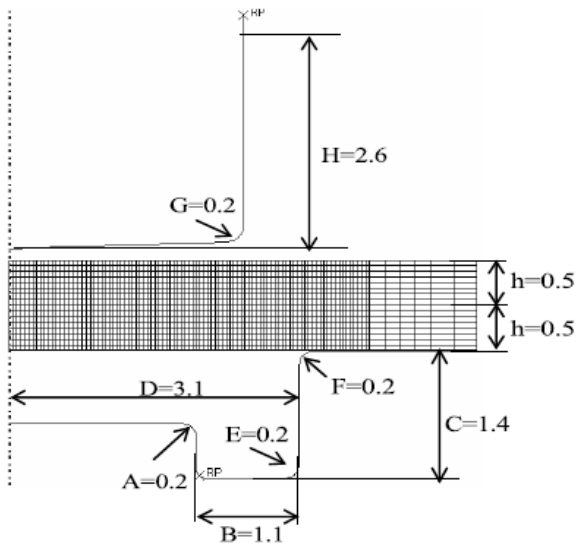
3 Results and discussion

3.1 Application to clinch joining of sheets

The sheets are made of an aluminium alloy AL5754, 0.5 mm thick each. The material properties are: $E = 70$ GPa, $\nu = 0.3$. Isotropic hardening law $\sigma_{eq} = 627(0.023 + \epsilon_p)^{0.31}$ (MPa) is adopted. Coulomb friction model is assumed in this problem with $\mu = 0.1$ for the friction coefficient between the sheets and the tools, and $\mu = 0.35$ for the friction coefficient between the sheets.

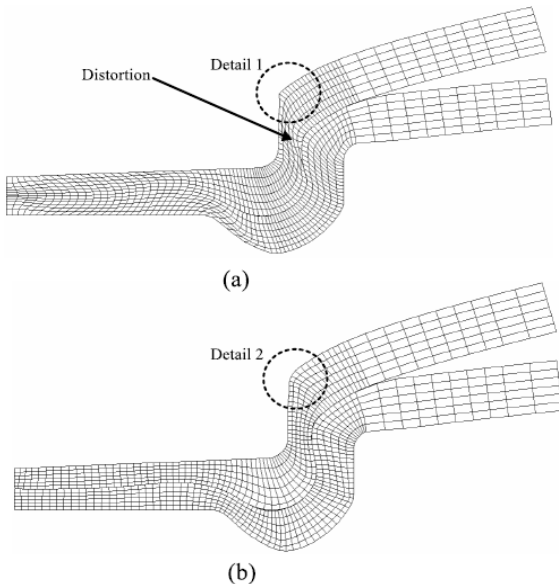
The numerical simulation is carried out using an axisymmetric model with a dynamic explicit approach of ABAQUS software. The blanks are meshed using a quadrilateral axisymmetric element (element CAX4R of ABAQUS), involving 808 elements for each blank. The tools (punch and die) are assumed to be analytical rigid (Figure 3).

Figure 3 Schematic illustration and FE model of the clinched joints studied



This application involves a large deformation of sheets. High local plastic strains are developed during the clinching operation, resulting in severe local mesh distortion (Figure 4a). In order to obtain an accurate clinched joint shape, the adaptive meshing technique is used (Figure 4b). On the other hand, small time steps are adopted to obtain an accurate solution, in particular, during the separation step (Figure 5).

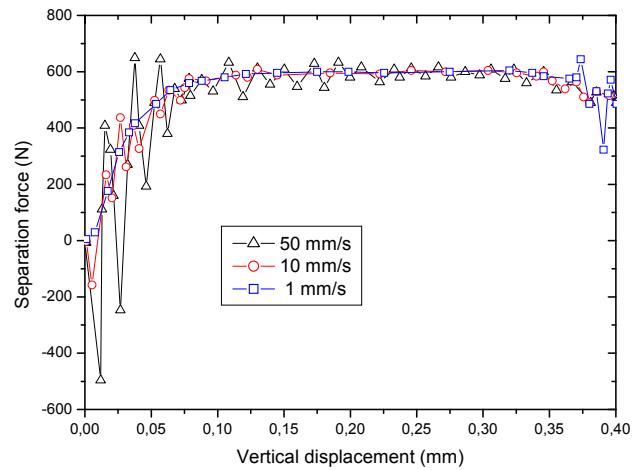
Figure 4 Deformed meshes: (a) without re-meshing, (b) with re-meshing



The FE-analysis includes two simulation stages:

- 1 *Clinching operation.* In this stage the simulation is made by moving the punch until the reduction of the sheets thickness reaches 60%.
- 2 *Separation step.* In order to evaluate the tensile force of the joint (vertical force), the sheets are loaded in the vertical direction, until obtaining their complete separation.

Figure 5 Separation force displacement as a function of separation speed (see online version for colours)

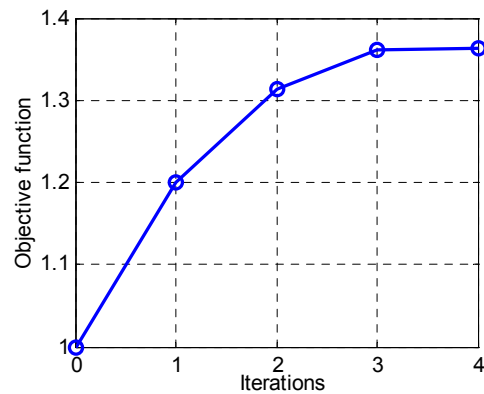


3.2 Optimisation results and discussion

In order to compute the maximum tensile force of the clinched joints, Finite Element Method (FEM) simulations were run after the shape of the tools had been updated according to the optimisation results.

The evolution of the objective function during the optimisation procedure is presented in (Figure 6). It can be observed that RSM techniques give significant improvement of the clinched joints' tensile strength force. The optimal solution is obtained starting from the third iteration. The objective function is then increased by 37%.

Figure 6 Evolution of the objective function during the optimisation iterations (see online version for colours)



The optimisation strategy adopted clearly showed its capacity to improve the strength of the joint above that previously achieved using Moving Least Squares (MLS) approximation. The reason is that the kriging interpolation is more accurate and is improved by increasing the number of evaluation points in the vicinity of the optimum. Note that the die groove width (variable B) and punch radius (variable G) change and reduce to 0.82 mm and 0.10 mm (Figure 7a and Figure 7c), respectively. On the other hand, the die diameter (variable D) is significantly increased (Figure 7b). It shifts from 3.0 mm to 3.28 mm.

Figure 7 Evolution of the optimisation variables during the optimisation iterations (see online version for colours)

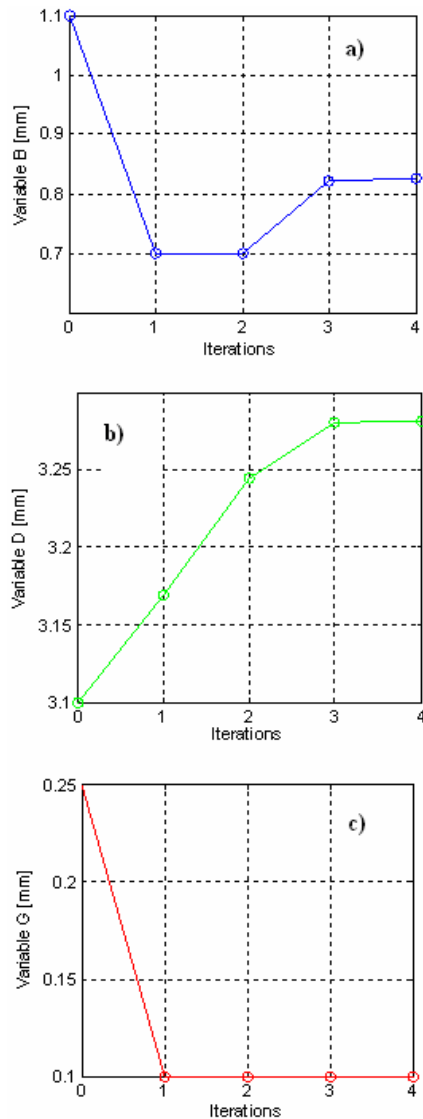


Table 1 summarises the results obtained with the initial and optimal tool shape design. It can be seen that the strength of the clinched joint increased significantly when optimised using the kriging interpolation compared to the non-optimised joint. It increased from 623 N to 834 N. The use of MLS approximation in previous work also showed improvement of the strength of the joint but was still lower than that obtained using the kriging interpolation.

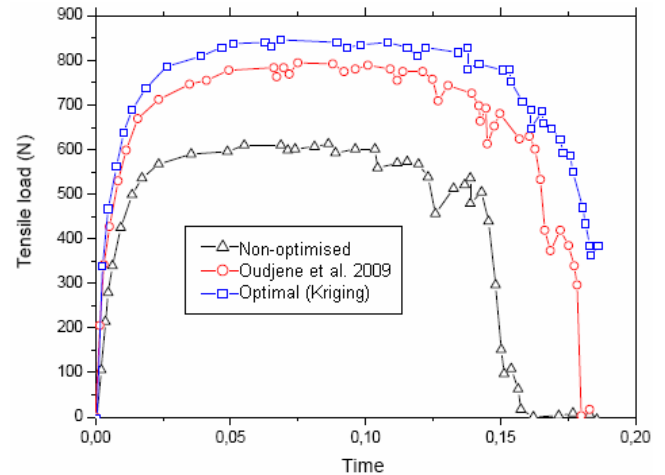
Table 1 Parameters before and after optimisation

Parameters	min	max	initial	optimal
B (mm)	0.70	1.20	1.20	0.82
D (mm)	3.00	3.30	3.10	3.28
G (mm)	0.10	0.40	0.25	0.10
J (%)	–	–	100.00	137.16

Figure 8 shows the tensile force curves obtained during the separation step for initial and optimised tool geometry. It can be observed that the load carrying capacity of the

clinched joints is significantly improved by optimising the tool geometry. It was increased by 10% when compared to that previously achieved using the MLS approximation (Oudjene et al., 2009). The optimisation strategy clearly showed its capacity to obtain a better optimal solution with a very fast convergence.

Figure 8 Tensile loads versus time during the sheet separation: comparison between optimised and non-optimised joints (see online version for colours)



4 Conclusion

The aim of this paper was to optimise the tool geometry of the clinch forming process towards the improvement of clinched joints' tensile strength. An improved and automatic optimisation procedure, based on RSM and SQP programming methods, is proposed and implemented in ABAQUS finite element code. The response surfaces are built using kriging interpolation. In order to improve the RSM accuracy and to deal with the local optimum problem, an efficient optimisation strategy allowing the updating of the search space is presented. The optimisation procedure leads to very satisfactory results and allows further improvement of the clinched joints' strength to that previously achieved. In fact, the use of the kriging technique seems to be efficient when the objective function presents several optima. This work is an improvement on previous one presented in Oudjene and Ben-Ayed (2008) and Oudjene et al. (2009). The optimisation procedure developed will have extensive applications and can also be helpful in designing various forming processes.

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