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QUALITY ANALYSIS OF CLINCHED JOINTS VIA IMAGING AND COMPARISON WITH FORMING SIMULATIONS

Gabriel Martinelli Zapata, gmzapata@fem.unicamp.br[1]
Alexandre Luis Marangoni, alexandremarangoni@yahoo.com.br[2]
Marcelo Quartiermeister, mvquarti@yahoo.com.br[3]
Rafael Sottili Chaves, rafaelsottili@gmail.com[4]

[1]Faculdade de Engenharia Mecânica - UNICAMP, Rua Pereira Landim, Centro, CEP:14.940-000, Ibitinga-SP,
[2]Whirlpool S.A., Jardim Portugal, CEP:13.504-060, Rio Claro-SP,
[3]Escola Politécnica da Universidade de São Paulo - USP, Jardim Bela Vista, CEP: 13.504-269, Rio Claro-SP,
[4]Centro Tecnológico - UFSC, Campus Universitário Trindade, CEP: 88040-900, Florianópolis-SC.

Abstract*. The mechanical union process of clinched joints has been widespread in the last decade as an alternative to spot welding and fasteners in general. Joints quality and strength are dependent of material properties, dimensional characteristics and manufacturing parameters. It is worth mentioning the importance of sheet metal forming simulations as a method to avoid trials and errors in manufacturing processes. The objective of this study was to verify the correlation between a real clinched joint with the finite element simulation results. Design of experiments (DOE) methodology was used to conduct the investigations regarding influence of the material properties, sheet thickness and process factors for a real clinched joint. The final dimension, cracks presence and poor fill of undercut's geometry were considered as responses. A computational DOE was carried out including some noise factors, such as friction coefficient and die clearance. The real joint final dimension, measured via optical microscopy, was compared with the simulated results.*

Keywords*: Press-Joining, Finite Element Method, Optical Microscopy Analysis.*

1. INTRODUCTION

The clinching process consists of a holding system in which two or more plane entities are joined through a deep drawing geometry generated by a die-punch assembly. Nowadays it has become a joint technology extensively adopted in industry according to Rietman et al. (2001).

The joint mechanical strength is strictly related to tools geometry and the material of the sheets to be formed. Therefore the tooling project must be customized in accordance with material parameters and thickness of the sheets involved in the clinching process.

Shi et al. (2012) and Rietman et al. (2001) highlight that the clinching process parameters specification is not an easy task, and so it is very important to associate the process practical knowledge to tooling using mathematical models and Finite Element Method (FEM).

Initial practical experiments are important to achieve knowledge gain and mapping of process, parameters, variation sources and noises. Taking mapping into account, it is possible to plan experiments according to 6 sigma methodology and evaluate a correlation between physical and computational experiments. One can expect that noisy results will be achieved, however 6 sigma methodology must guarantee results refinement and a reliable model.

Rietman et al. (2001) also point out that a FEM ensures a robust development, mainly regarding structural performance requisites more and more critical.

In the current study controlled specimens of different materials and thicknesses were manual clinched with different conditions of prototyped tooling. A correlation between Finite Element Analysis (FEA) and physical clinched joints was carried out regarding some design parameters of a clinch point. Due to industrial secret issues, some critical information was not allowed to be published and was omitted.

2. MATERIALS AND METHODS

A full factorial DOE with 64 treatments was carried out to evaluate the importance of the parameters related with the clinching forming process. The selected parameters were the upper sheet material type, upper and lower sheet thicknesses, friction coefficients, tool wear condition and tool travel. The levels of the parameters are showed at the Tab. 1, where the steel grade was suppressed due industrial secret issues.

The parameters configurations of each experiment treatment are presented at the Factor Relationship Diagram (FRD), showed at Fig. 1, which also shows possible sources of variation, as solver precision, software version, the blank and tools initial element size (0.1 mm), adaptive mesh refinement (0.07), simulation end time (0.5 s), LS-Dyna general controls and database keywords, blank holder force (1500 N) and tool materials.

The Altair HyperMesh® software was used to create the finite element model considering the parameters configuration for each experiment treatment. The solution was carried out using the LS-DYNA R 8.0 solver. The simulation post processing, performed using the Altair HyperView® and LS-PrePost 4.0® software, had consisted in the measurement of the dimensions showed at Fig. 2.

Another answer that was evaluated in the computational DOE was "max_GAP", as shown in Fig. 3 (b). It was taken as an important answer because some micrographs revealed a pronounced gap between lower and upper sheet at necking region that led to cracking, as it can be seen in Fig. 3 (a).

Table 1. Description of DOE factors and the corresponding evaluated levels.

Parameter	Level "-"	Level "+"
Upper Sheet Material	Galvanized Steel	Structural Steel
Upper Sheet Thickness	1.15 mm	1.35 mm
Lower Sheet Thickness	0.5 mm	0.7 mm
Friction Coefficients	Static 0.3 & Dynamic 0.13	Static 0.7 & Dynamic 0.3
Tool Wear Condition	New tool	Old tool
Tool Travel	2.705 mm	3.175 mm

The DOE analyses were performed using the SAS JMP 11.0 data analysis software.

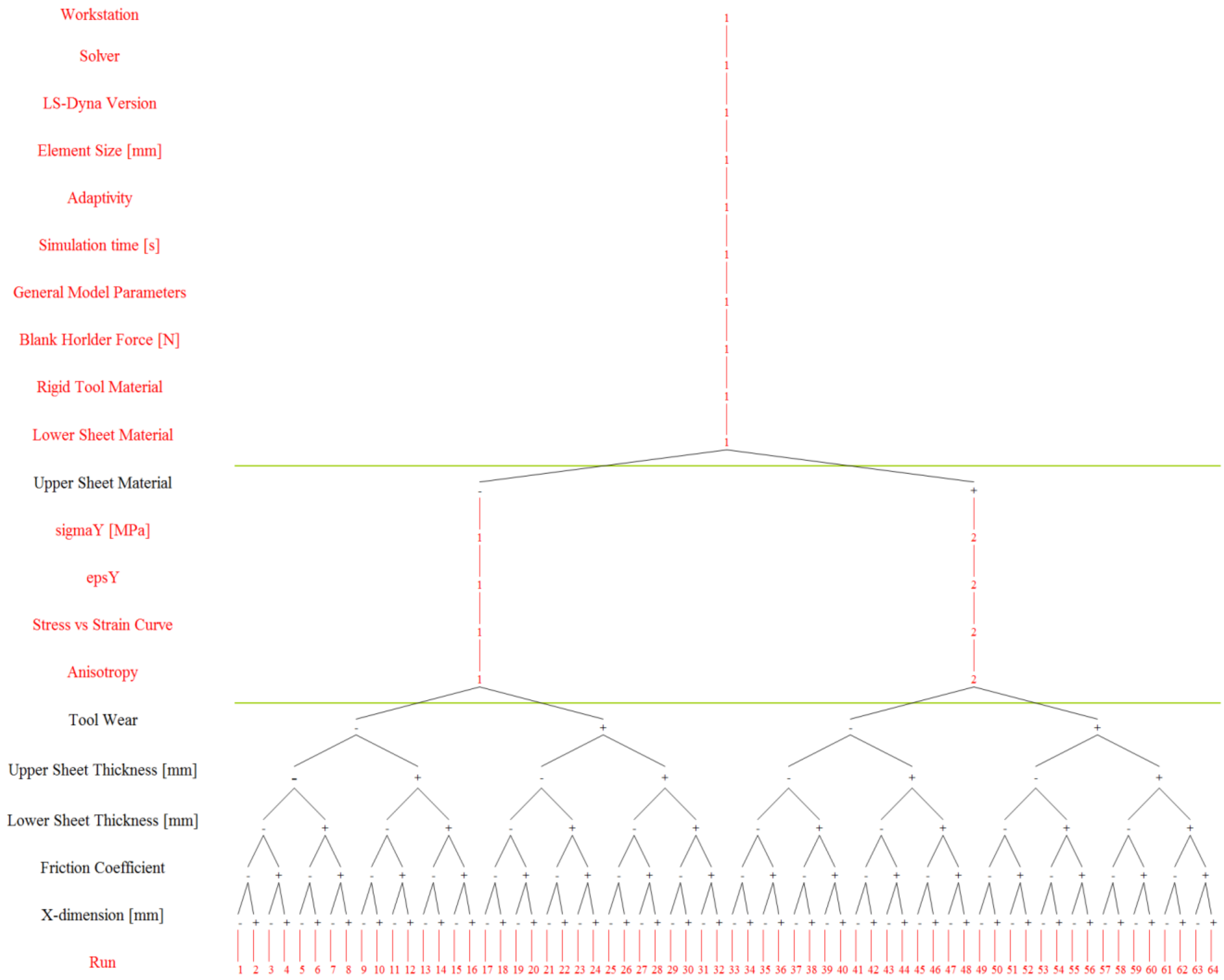

Figure 1. Factor Relationship Diagram used in the current study for computational clinched joint simulations.

Controlled specimens of different materials and tool conditions were manual clinched for experimental evaluation and computational correlation. Optical micrographs of clinched parts were performed at Whirlpool Material Laboratory using a Media Cybernetics® camera Evolution LC Color attached to a Wild Heerbrugg microscope. The specimens were cut and wet ground to reveal the clinched materials and, more specifically, the dividing line between the two sheets. The measurements of formed joints were captured at Image-Pro Express, as showed at Fig. 4.

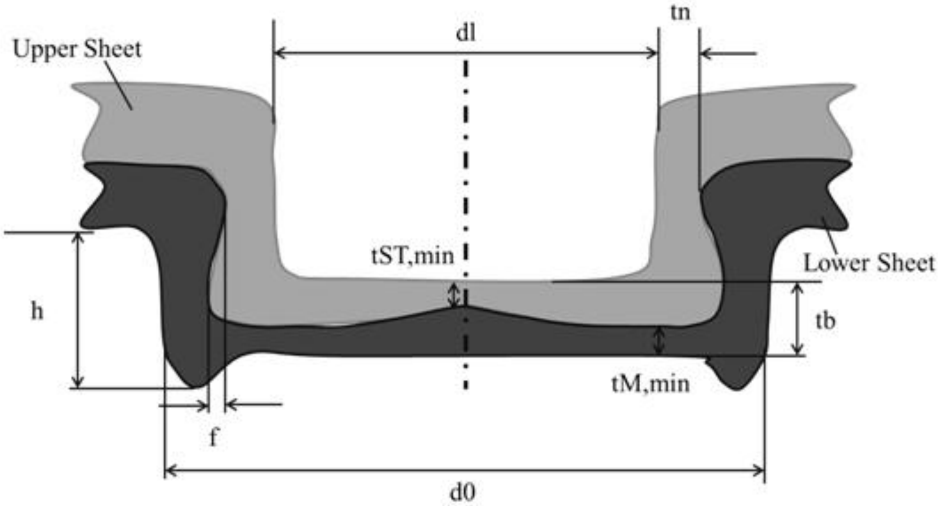

Figure 2. Evaluated measures as the DOE answers of the current study.

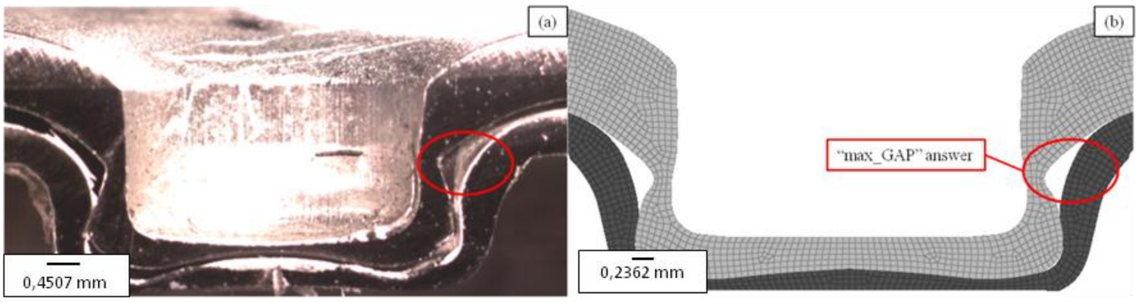

Figure 3. (a) Pronounced gap between upper and lower sheets revealed by micrograph of physical parts and (b) computational "max_GAP" answer that was taken for DOE analysis.

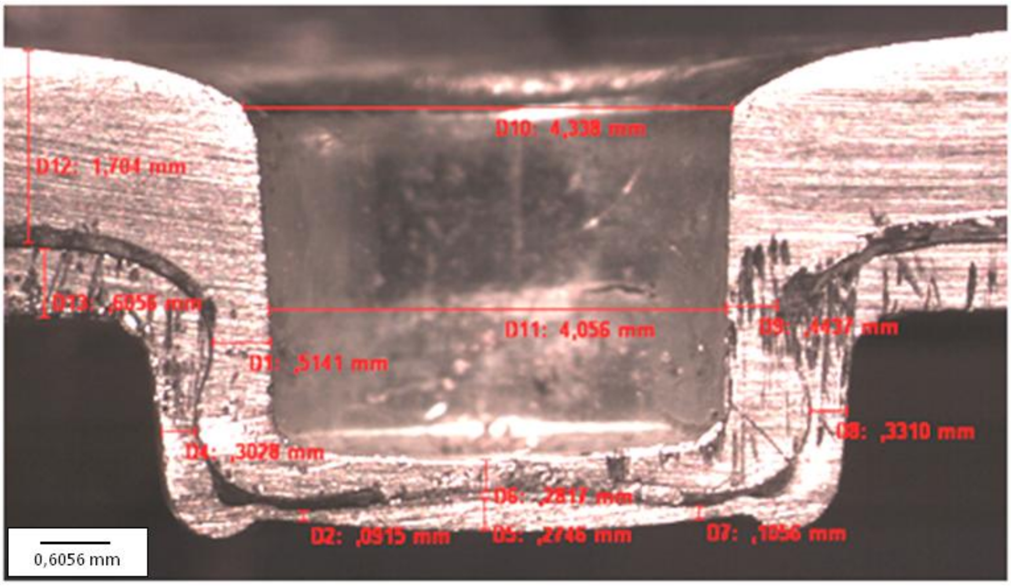

Figure 4. Optical microscopy of clinched joint with some critical measures highlighted.

Correlation between the real and the finite element simulation clinched joints was evaluated by image overlay and by measuring some critical dimensions.

3. RESULTS AND DISCUSSION

The first work consisted of creating a Finite Element Model (FEM) of a clinched joint with prototyped tolling geometry and comparing the computational results with physical joints. The reason to start with this methodology was to check the model capability to preview the real clinching condition. One of the established comparisons was made by image overlay, as it can be seen in Fig. 5, and a satisfactory correlation has been obtained.

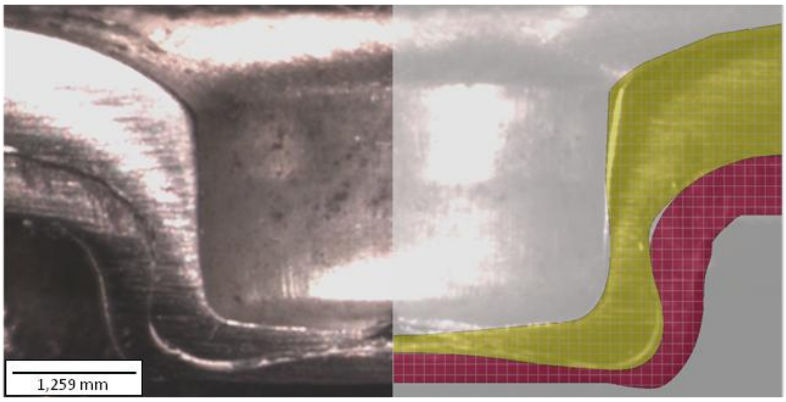

Figure 5. Image overlay of physical and computational (yellow and red) clinched joint.

After image overlay comparison, a statistical analysis was carried out via variability charts to check the divergence between the 64 computational DOE answers (FEA method) of “tn”, “dl”, “f” and “tM,min” and the correspond measurements of 15 real clinched parts (Experimental method).

Figure 6 shows the variability charts for the dimensions “f” (a), “tM,min” (b), “tn” (c) and “dl” (d) obtained from the clinching joints specimens (Experimental) and via forming simulation (FEA). A good correlation, denoted by the similarity of the resulting distributions, could be observed for the dimensions “f”, “tM,min” and “tn”. A small difference between the experimental and simulated data could be observed at “dl” dimension, which could be attributed to an offset at central location at cutting process of the sample preparation.

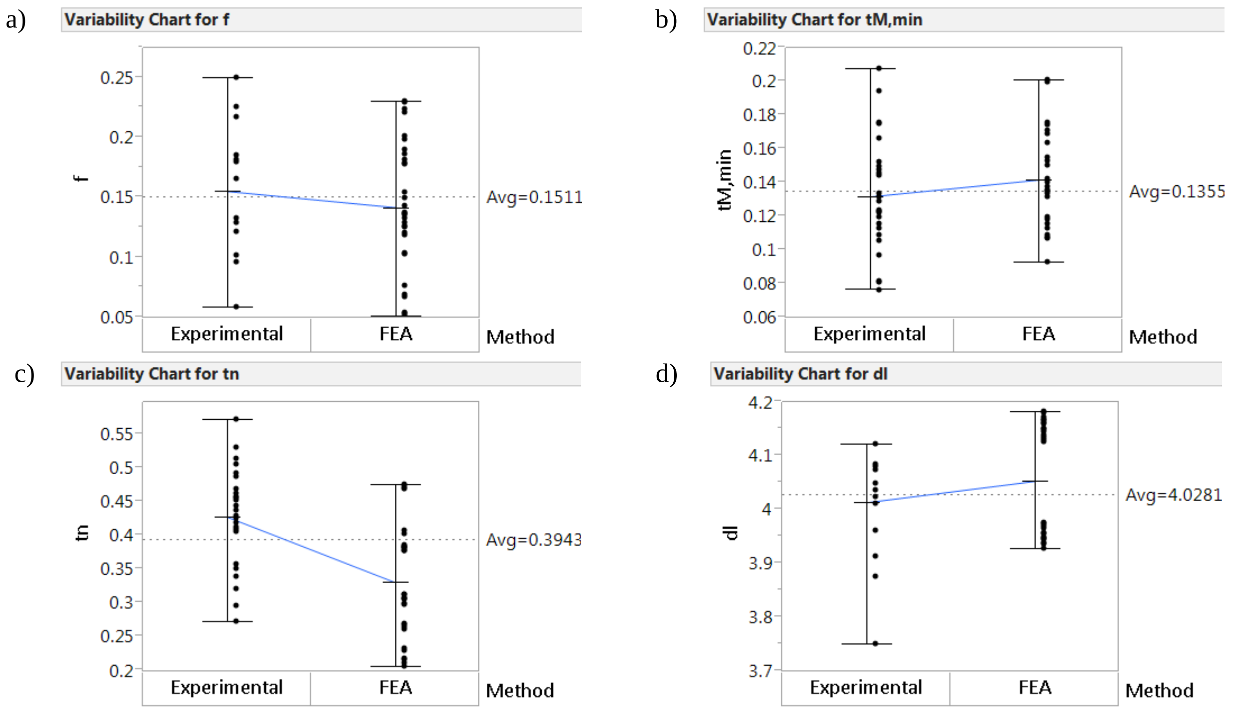

Figure 6. Variability charts for the DOE answers (a) “f”, (b) “tM,min”, (c) “tn” and (d) “dl”, establishing a comparison between Experimental and Finite Element Analysis (FEA) methods.

Pareto Plots of Estimates were created to evaluate statistically which factor or interactions between factors have the most evident influence for each computational experiment answer.

Taking "h" as measured answer, it can be said, according to Fig. 7, that the most influent factors were upper sheet thickness (G), lower sheet thickness (C), tool wear (T) and tool travel (X). There is no important influence of the upper sheet material and friction coefficient regarding "h" answer.

One can say that the higher the lower sheet thickness, the higher the "h" value will be because the measure reference is the surface in contact with the die.

The higher the upper sheet thickness, the higher the "h" value will be due to a greater amount of material to form the lower sheet against the die, contributing to better filling of undercut region.

The more intense tool wear, the higher the "h" value will be because the material loss led to a gap between punch and die and, consequently, a larger depth to form the joint.

The increase in tool travel leads to a higher "h" value measure because more material will be formed and compressed against the die, flowing toward undercut region.

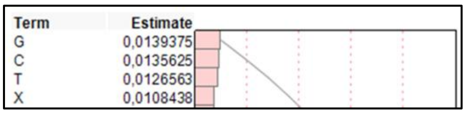

Figure 7. Pareto Plot of Estimates for "h" answer.

Taking "f" as measured answer, it can be said, according to Fig. 8 (a), that the most influent factors were tool travel (X), lower sheet thickness (C), the second-order interaction between tool wear (T) and friction coefficient (F), and upper sheet material (M). The upper sheet thickness has no influence regarding "f" answer.

The higher the tool travel, the higher the amount of upper sheet material that will be formed against the lower sheet, leading to a more pronounced undercut.

The higher the lower sheet thickness, the higher the "f" value. Given that the tool geometry restricts the flow of material to an already defined path of conformation and that there is no thinning of the sheet in contact with the die (lower sheet) up to the region of necking, increasing the thickness of the lower sheet will result in a larger delta between the necking and the above region, leading to a higher "f" value.

There is an interaction between wear of tooling and the friction coefficient between the parts. We can observe that for higher values of friction coefficient, that can be associated with surface roughness or lubrication, there is a smaller variation of the "f" value. For lower friction coefficients, the tool wear gives an "f" value of approximately 0.05 more pronounced when compared to a new tool, which is also related to the fact that you have more space available for forming of the material.

When the tool is in a new condition, an increase of the friction coefficient will lead to an increase in the "f" value. When the tool shows significant wear, an increase in the friction coefficient will reduce the "f" value.

For this measured value, the type of material did not show significant influence. It is possible to observe a slight increase in the "f" value when using structural steel, in which the higher yield strength allowed a higher compression of the lower sheet.

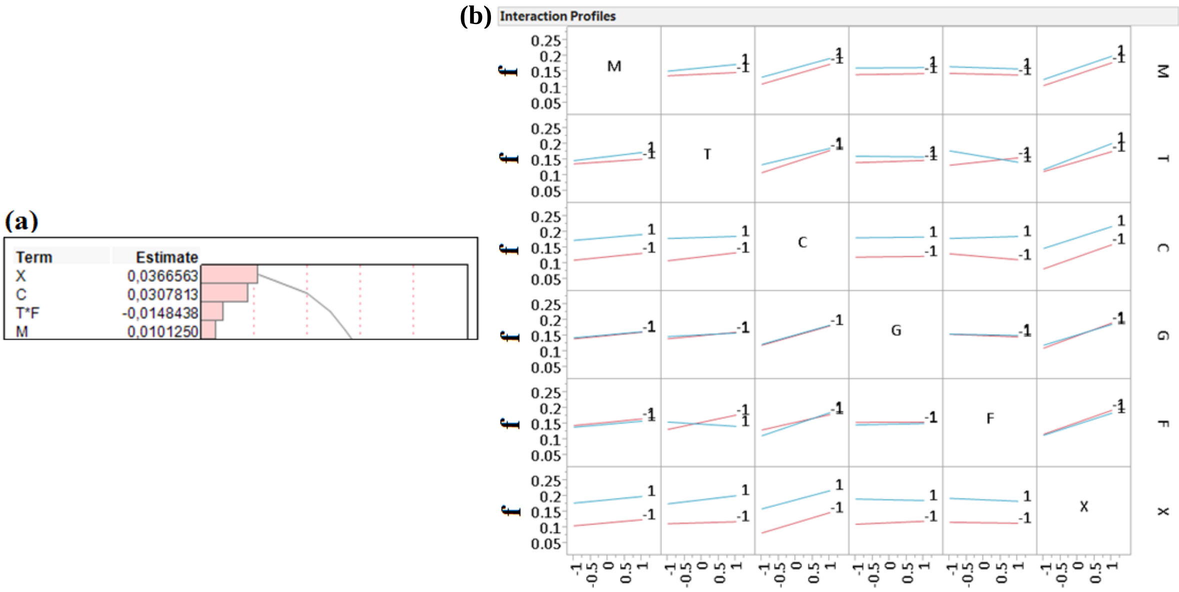

Figure 8. (a) Pareto Plot of Estimates and (b) Interaction Profile between factors for "f" answer.

Taking “tb” as measured answer, it can be said, according to Fig. 9, that the most influent factors were tool wear (T) and tool travel (X). Upper sheet thickness, friction coefficient, material and lower sheet thickness have no influence regarding “tb” answer.

The higher the tool wear, the higher the “tb” value will be. This is due to the fact that both punch and die present loss of material, which leads to an increase in the gap of the tool, having impact in the “tb” value.

The “tb” value is directly related with the tool travel (X). The larger the X value, the higher the compression between the sheets, which implicates in a smaller thickness of the bottom of the joint.

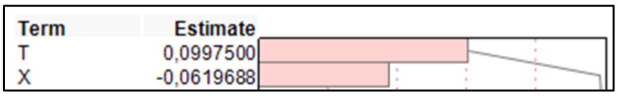

Figure 9. Pareto Plot of Estimates for “tb” answer.

Taking “tST,min” as measured answer, it can be said, according to Fig. 10, that the most influent factors were tool wear (T), tool travel (X) and lower sheet thickness (C). Upper sheet thickness, friction coefficient and material have no influence regarding “tST,min” answer.

The larger the tool wear, the larger the gap between tools will be. This will lead to an increase in the thickness of the bottom of the joint, which will cause an increase in "tST,min" as well.

Tool wear has an effect that it can´t appropriately compress both sheets. This effect is more pronounced in the upper sheet.

An increase in tool travel causes a reduction in the “tST,min" value. This is caused by the fact that we will have a larger quantity of material of the upper sheet flowing in a radial direction, leading to a thickness reduction of the upper sheet in the "tST,min" region.

Higher thicknesses of the lower sheet will lead to smaller "tST,min" since the material has a tendency of flowing in a radial direction. In the center line, the lower sheet already presents the highest thickness in the bottom of the joint, leading to minimum thickness of the upper sheet.

Both upper sheet thickness and material did not have influence in "tST,min" values.

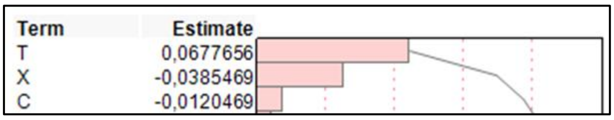

Figure 10. Pareto Plot of Estimates for “tST,min” answer.

Taking “tM,min” as measured answer, it can be said, according to Fig. 11, that the most influent factors were lower sheet thickness (C), tool travel (X), upper sheet thickness (G) and tool wear (T). Friction coefficient and upper sheet material have no influence regarding “tM,min” answer.

For higher lower sheet thicknesses it was observed higher values for "tM,min". Since the strain occurs in consequence of a given punch travel or displacement previously imposed one can infer that, for a given displacement, the higher the thickness of the lower sheet, the higher is the amount of material left over in the bottom of the joint.

Lower values for "tM,min" were shown with increase in tool travel. This is related to the fact that forming and thinning of the region are more pronounced.

The higher the thickness of the upper sheet, the lower the "tM,min" value will be due to the fact that the higher quantity of material of the upper sheet will push and strain more material of the lower sheet.

More pronounced wear of the tolling showed higher "tM,min" values since wear leads to loss of material of the tool and increases gap between die and punch.

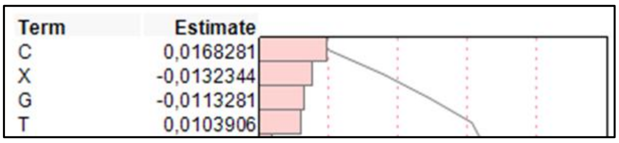

Figure 11. Pareto Plot of Estimates for “tM,min” answer.

Taking “tn” as measured answer, it can be said, according to Fig. 13 (a), that the most influent factors were tool wear (T), upper sheet thickness (G), lower sheet thickness (C), friction coefficient (F) and the second-order interaction between tool wear and friction coefficient. Materials of upper sheet and tool travel have no influence regarding “tn” answer.

The higher the tool wear, higher necking occurs and smaller is the “tn” value. The cracks normally occur in this region, as seen in the micrographs, due to excess thinning generated by the process. One can conclude that the tool geometry is intimately related with this value and probability of showing cracks. Figure 12 shows a probable case where wear of the tool caused cracks in the final joint.

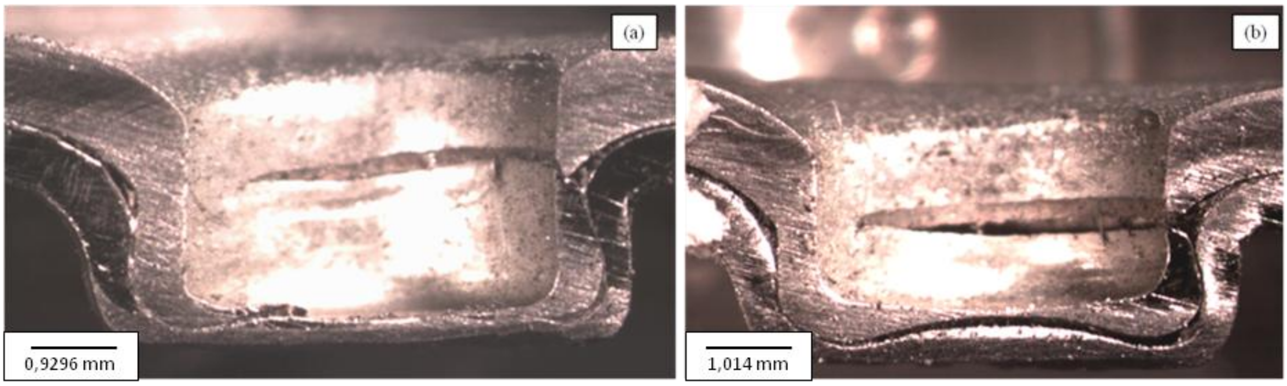

Figure 12. Two cases of cracked joints due to excessive thinning at necking region.

Higher thicknesses of the upper sheet will result in larger “tn” values since the geometry of the tool is set and non-deformable and the flow of material already has a pre-defined and limited route.

Higher thicknesses of lower sheet will lead to lower “tn” values. In this region we do not observe thinning of the lower sheet because it is a region above the necking. In having a higher lower sheet thickness, the sheet will push more material of the upper sheet and lead to more pronounced thinning.

Higher values of friction coefficient led to higher values of “tn”. The adherence between sheet and tool is greater when friction coefficient is larger. This leads to smaller degree of thickness reduction in the region since the flow of material is diminished.

Regarding T*F interaction, in a new tool there is no significant difference in “tn values having an impact in the values of the friction coefficient. However, in a tool with significant wear, higher coefficients will lead to higher “tn” values.

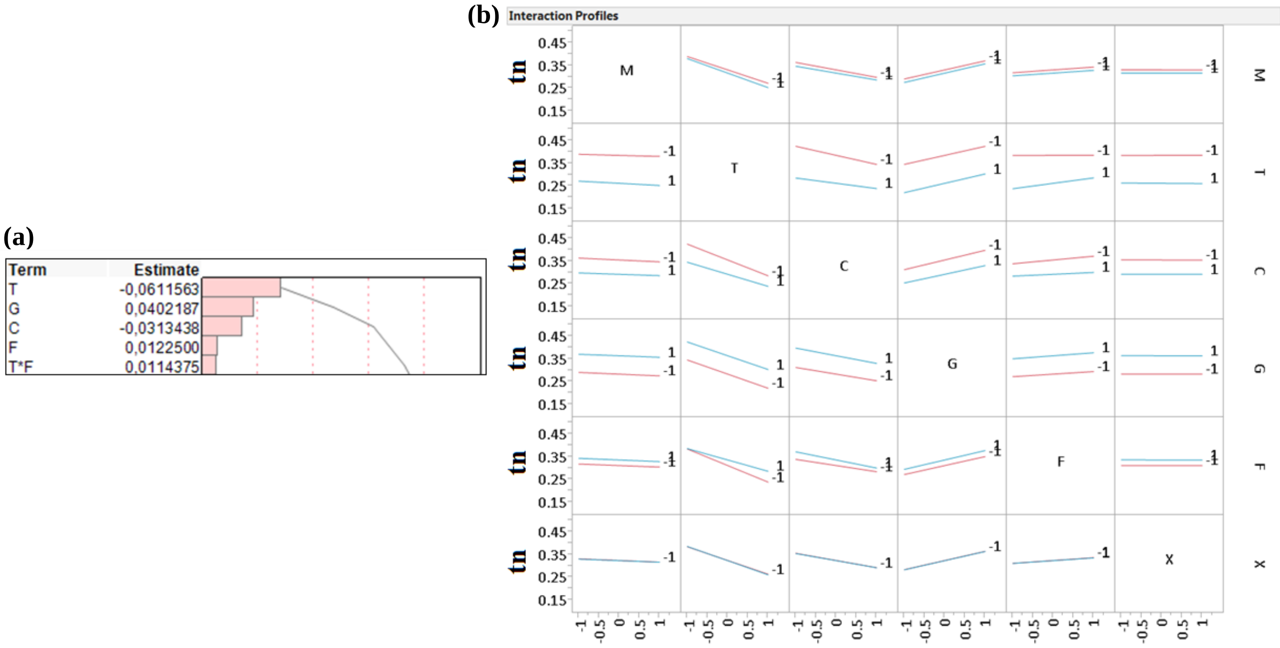

Figure 13. (a) Pareto Plot of Estimates and (b) Interaction Profile between factors for “tn” answer.

Taking “d0” as measured answer, it can be said, according to Fig. 14, that the most influent factors were tool travel (X), lower sheet thickness (C), upper sheet thickness (G) and tool wear (T). Friction coefficient and material of upper sheet have no influence regarding “d0” answer.

The "d0" diameter increases with larger tool travel since more material will be pushed against the die and have a greater tendency of filling the empty spaces of the die with the larger flow of material in the direction of the bottom of the joint (die cavity).

Higher lower sheet thickness lead to higher "d0" values. This occurs because there is more material of the lower sheet to flow in radial direction and fill all die cavities. Higher upper sheet thicknesses also lead to higher values of "d0". In this case we have a larger quantity of upper sheet material that tends to push more material of the lower sheet.

A new tool produces points with larger "d0" values. This happens because the loss of material generated by the wear of the tool increases the gap between tools and there is not a complete filling of the die cavity.

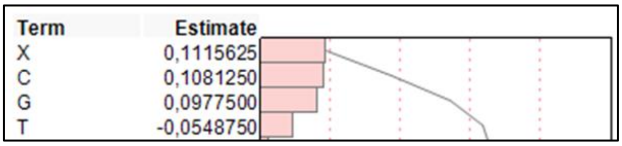

Figure 14. Pareto Plot of Estimates for "d0" answer.

Taking "dl" as measured answer, it can be said, according to Fig. 15, that the most influent factors were tool wear (T) and upper sheet thickness (G). The lower sheet thickness, punch travel, friction coefficient and material of upper sheet have no influence regarding "dl" answer.

Tool with pronounced wear (T+) lead to smaller "dl" since the wear also leads to loss of radial material of the punch.

Higher upper sheet thickness produces higher values for "dl".

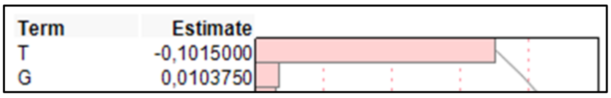

Figure 15. Pareto Plot of Estimates for "dl" answer.

Taking "max_GAP" as measured answer, it can be said, according to Fig. 16, that the most influent factors were tool wear (T), friction coefficient (F), lower sheet thickness (C) and upper sheet thickness (G). Punch travel and material of upper sheet have no influence regarding "max_GAP" answer.

Tools with pronounced wear generate larger "max_GAP" values due to filling of the die cavity and loss of radial material of the punch.

Higher friction factor will impact in smaller "max_GAP" due to higher adherence between sheet and tool.

Increase in both upper and lower sheet thicknesses will result in smaller "max_GAP". For the lower sheet this is due to the fact that, in the region above the "undercut" region, the lower sheet does not suffer thickness reduction. Since the "max_GAP" is measured above this region, its values will be smaller with increase in lower sheet thickness. For the upper sheet the behavior is explained due to the fact that we have a larger quantity of upper sheet material to fill this measured "GAP".

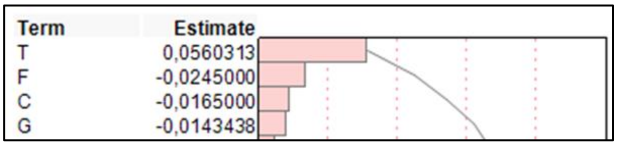

Figure 16. Pareto Plot of Estimates for "max_GAP" answer.

Taking "rcforc_dyna" as measured answer, it can be said, according to Fig. 17, that the most influent factors were tool wear (T), punch travel (X), lower sheet thickness (C), friction coefficient (F), upper sheet thickness (G), material of upper sheet (M), the second-order interaction between tool wear and tool travel, the second-order interaction between tool wear and lower sheet thickness, the second-order interaction between tool wear and upper sheet thickness, the second-order interaction between lower and upper sheet thicknesses, and the third-order interaction between tool wear, lower sheet thickness and upper sheet thickness.

Pronounced wear of tool results in smaller "rcforc_dyna". Since there is a larger gap between tools, which is a result of loss of material, there will be less strain.

The larger the tool travel ("X"), the larger the "rcforc_dyna" will be. The resistance to flow of the material to the die cavity will increase with the amount of strain imposed.

Higher upper and lower sheet thicknesses result in higher "rcforc_dyna" once a greater strain resistance exists imposed by the higher thicknesses in result of the larger quantity of material to be pushed.

Higher friction coefficients lead to higher "rcforc_dyna". There is a higher adherence that needs to be overcome during deformation to force material to flow in the tool cavity.

The use of structural steel increases "rcforc_dyna" due to the fact that structural steels have higher yield and tensile strengths to be overcome during forming.

When the tool is new, an increase in toll travel leads to an increase in "rcforc_dyna". On the other hand when we have a pronounced wear of the tool the increase in toll travel doesn't have great impact in "rcforc_dyna".

New tooling with higher lower sheet thickness leads to increase in "rcforc_dyna", but when tool shows signs of wear, the increase in lower sheet thickness does not show great significance in the same value. The same thing is seen with T*G interaction.

Since the upper sheet thickness is always higher than the lower sheet, the increase in upper sheet leads to larger increase in “rcforc_dyna" when compared to increases in lower sheet.

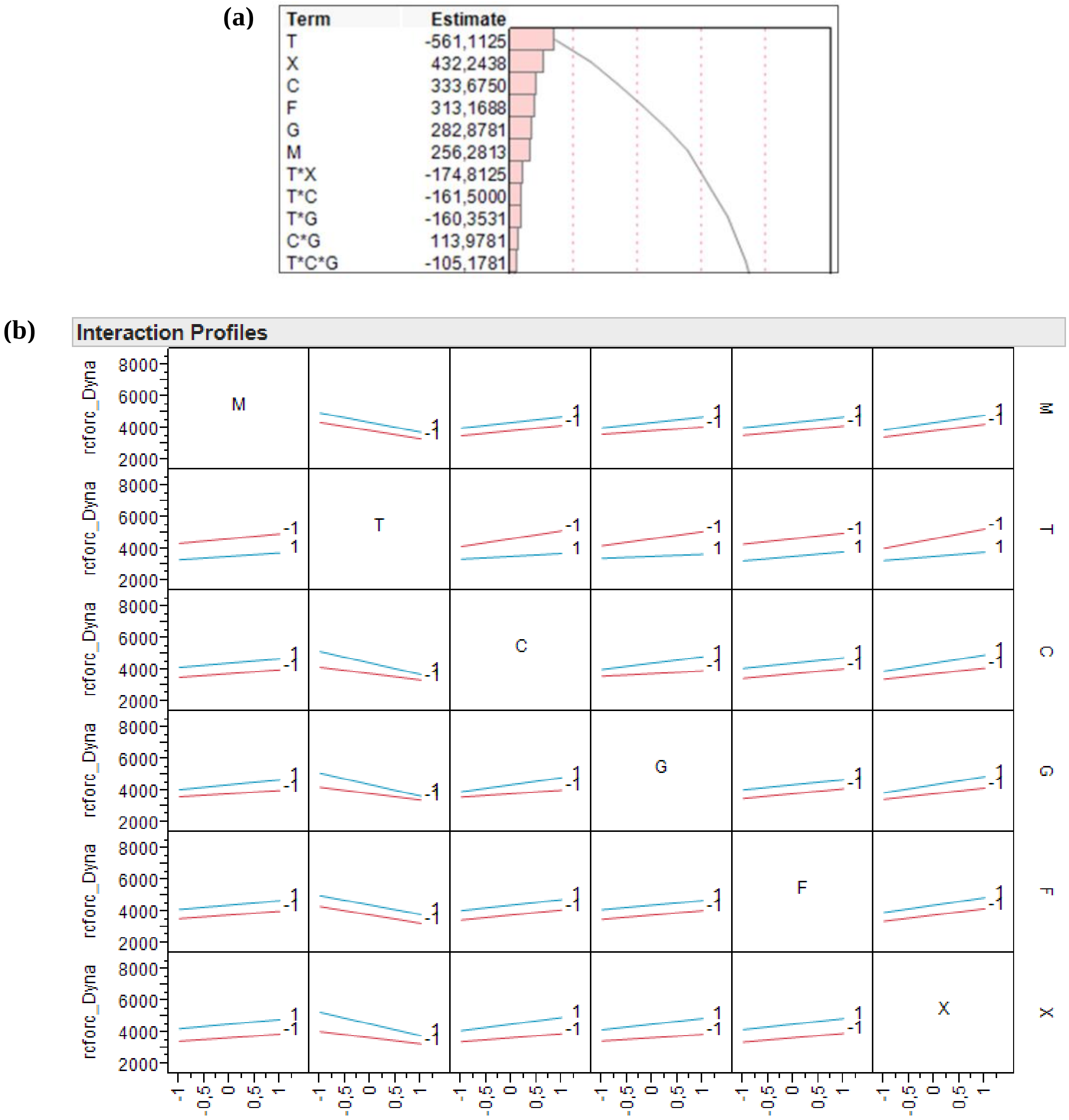

Figure 17. (a) Pareto Plot of Estimates and (b) Interaction Profile between factors for “rcforc_Dyna” answer.

4. CONCLUSIONS

The FEM could well represent the physical clinched joint as shown in image overlay of specimen micrograph and variability charts of some measured dimensions. Therefore, it is worth mentioning the importance of sheet metal forming simulations as a method to avoid trials and errors in manufacturing processes due to its very reliable correlation.

For the evaluated DOE answers, tool wear condition was the main factor of influence. That is the reason why preventive maintenance at production line is very controlled and carried out.

Punch travel and lower sheet thickness were other important factors in terms of design parameters of clinched joints considering the evaluated answers and factors levels.

The second-order interaction between tool wear and friction coefficient is important to point out. One can conclude that the lubrication can be valuable to guarantee quality when the wear of the tool increases.

As an outlook, the authors would like to evaluate the limit of materials in terms of crack appearance via computational DOE and impose a prototype condition in manual clinching to correlate the results.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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