DEFORMATION IN ALUMINUM ALLOY SKINS CAUSED BY RIVETING PROCESS

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Abstract. *The main objective of this work it to demonstrate experimentally the deformation effect in aluminum alloy skins when a riveting process is applied. The secondary objectives are: to determine which factors (hole diameter, depth of countersunk, rivet material, skin thickness and manual or automated riveting process) affect the skin deformation and the degree of this influence. Initially, a questionnaire has been sent to Riveting Process and Material Science specialists in order to identify the candidate factors to be further detailed and analyzed. The set of factors has been obtained through a Matrix evaluation technique. Then, it has been conducted an experimental approach based on the Taguchi Robust Design which has used the factors previously elected as well as a set of specimens. Finally, a variance analysis based on multifactor variance method has been done. The yielded results prove the expansion of panel after riveting process and identify the main factors of influence on this expansion.*

Keywords*: Deformation, Riveting, Experimental Project.*

1. INTRODUCTION

1.1. Difficulties in the Riveting Process of Aeronautical Industry

It was observed in the aeronautical industry that during the assembly of fuselages, some lateral panels always bears deformation of some millimeters in the extremities after installation of the rivets, resulting radius reduction of the panel bending. It has been set as a hypothesis that this phenomenon is associated with a deformation of the skin when the operation of riveting is performed. Considering that the skins are relatively extensive (approximately 5 meter length) with riveting lines of more than 100 rivets.

1.2. Hypothetical correlation between skin deformation and the riveting process

It has been carried out a finite element analysis of the riveting process (LI & SHI, 2003) and it has been detected that, when a rivet is installed, the hole suffers a small expansion (due to expansion of the rivet diameter), and the rivet pitch propagates approximately in a ratio of 1/10. Consequently, an expansion in the hole of the skin in 0.1mm would increase in 0.01mm on rivets pitch. A riveting line of 100 rivets will expected to have 1mm of increase, which matches approximately with the magnitude of the hypothetical phenomenon mentioned above regarding large size fuselages. However, application CAE (Computer Aided Engineering) software such Nastran^{TM} is not able to simulate plastic deformations that occur during the riveting process yielding only partial results as compared to the real effect.

1.3. Objective

This work has as main objective to perform an experimental analysis of the effect of deformation in aluminum skins when applied determined riveting process. The secondary objective is to identify amongst the eligible factors: hole diameter, countersunk height, rivet material, skin thickness and type of riveting - manual or automatic, those that can influence and the degree of its influence in the deformation of the skin.

2. Experimental Procedure

As the problem to be studied - effect of the deformation in skin aluminum due to the riveting process – has a lot of variables whose effect on the process is unknown, it is not feasible in practical terms, to perform an experiment for all them. So, the experimental procedure has been split in two phases, as follows:

- ✓ Choice of the factors

✓ Accomplishment of the experiment.

2.1. Choice of the variables (factors) of the experiment

It has been elaborated a questionnaire and an evaluation matrix to choose the most significant variables according to the experience and technical knowledge of specialists in riveting process and science of materials. As a result, eleven variables were chosen that might influence the phenomenon of skin stretching. They are:

1. Rivet material: the material of the rivet can be either Al2117 (70 Rockwell B) or Al7050 (147 Rockwell B); they present different mechanical behavior during the riveting due to the difference in its hardness.
2. Thickness of the skin: the most used thickness of skin in aeronautical industry varies from 1,5 mm up to 2,0 mm.
3. Gap before the riveting process: according to Aerospace Standard NASM 14219 (ANSI, 1999), the gap between the hole and the rivet before the riveting process (hole diameter minus rivet diameter) is expected to be from 0,09 mm up to 0,24 mm for a 5/32 inch hole diameter (3,96 mm).
4. Rivet type: two types have been considered - straight line or Brille (120º). Due to its geometry they can generate different standards of force (magnitude and direction) on the wall of the hole.
5. Rivet diameter: it can range from 2,4 mm to 7,9 mm.
6. Riveting sequence: the riveting sequence can intervene in the propagation of the deformation, mainly when the panels are fixed in gage points at tooling during the riveting process.
7. Type of riveting process (Manual versus Automatic): the manual process is performed in several cycles (or strokes) until the rivet is conformed to accomplish the technical specifications of rivet height and area head. The automatic process is performed in only one cycle (stroke).
8. Load of stamp machine: the load applied by the stamp machine can be adjusted during the riveting process (manual or automatic) and consequently, to intervene with the speed of deformation of the rivet and with the deformation exerted against the hole.
9. Load speed of stamp machine: the speed applied to the load of stamp machine can be adjusted during the process.
10. Countersunk height: in accordance to engineering specifications, the height of the countersunk can vary up to 0,89 mm for the 5/32 inch hole diameter (3,96 mm). To easy the measurement task, the height of countersunk is measured as the height of the rivet in relation to the surface of the sink. The higher the height of the rivet after the riveting, the lesser the height of countersunk.
11. Quantity of strokes of the stamp machine per hole: the amount of strokes intervenes with the height of the rivet and with the amount of material that is conformed within the hole. This variable is analyzed only for the manual riveting process.

After choosing the variables above, they were classified in two types:

1. Product Variable (PtV): they might intervene with the characteristics of the product, being able to modify its functionality. These are: Rivet material, type and diameter as well as the Thickness of the package.
2. Process Variable of (PsV): they might intervene with the characteristics of the riveting process, being able to modify the effectiveness and efficiency of the process. These are: Gap before the riveting (hole diameter minus rivet diameter), Sequence of riveting, Type of riveting (manual versus automatic), Load of stamp machine, Speed of application of the load of stamp machine, Countersunk height and the Quantity of strokes of stamp machine per hole.

The variables “Rivet type” and “Rivet diameter”, by consensus of the specialists, are specified to attend aeronautical functionalities such as aerodynamics and fatigue endurance. Thus, they were considered as preconditions for the experiment being set as follows:

✓ Rivet type: Brille (120º) – it is more frequently used in the national aeronautical industry due to its good sealing characteristics.

✓ Rivet diameter: the 5/32 inch (4,0 mm) diameter is more frequently used in the national aeronautical industry.

The variables “Load applied in the stamp machine” and “Load Speed of the stamp machine” had been considered as derived from the variable “Type of riveting” because these are the main characteristics that differentiate the riveting processes. Whether a complementary analysis of the variable “Type of riveting” is found necessary, then the two variables might be further analyzed.

A four-level criterion has been used to elaborate the evaluation matrix, namely: (1) Irrelevant, (2) Little Relevant, (3) Relevant and (4) Very Relevant.

Each respondent (process specialist) has evaluated each variable separately and the final evaluation has been calculated through the product of the individual evaluations divided by a factor 1000 to normalize the comparison between the numbers obtained, according to Eq.1.

$$Px = \left(\prod_{i=1}^{n} Pi\right)/1000 \quad , \text{i} = 1, 2, ..., 8 \qquad (1)$$

where Px is the final evaluation of variable x and i corresponds to each respondent.

In order to minimize even further the cost of the experiment, it has been decided to limit the maximum amount of variable to five; these were chosen based upon the final evaluation score (Px) as presented and highlighted in Tab 1.

It was analyzed too the easiness in applying improvements in the variable, in case that its influence in the phenomenon is detected, in order to get results more significant for the Manufacturing area. In case that two or more factors present evaluation value very next to each other, the easiness of improvements implementation in the factors will be taken as decision criterion.

As this theme is a subject unknown, the multidiscipline team made the decision to work with saturated combinations, that is, all the possible combinations for all the variables.

Table 1 – Variables Evaluation Matrix (adequar notação de PtV e PsV em amarelo)

N	**Evaluators/ Variables**	PtV/PsV	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Px**
1	Rivet material	PtV	8	8	8	8	8	8	4	4	524.29
2	Thickness of the package	PtV	8	4	8	4	4	4	4	4	65.54
3	Gap before riveting process	PsV	8	8	8	8	8	8	8	4	1048.58
4	Rivet type	PtV	2	4	2	1	1	2	2	4	0.13
5	Rivet diameter	PtV	1	8	8	8	8	8	4	4	65.54
6	Riveting sequence	PtV	2	1	4	2	2	2	1	4	0.13
7	Type of riveting process	PsV	4	4	2	4	4	2	4	8	16.38
8	Load of stamp machine	PsV	4	4	2	4	4	2	2	8	8.19
9	Load speed of stamp machine	PsV	2	2	2	4	2	2	8	8	4.10
10	Countersunk height	PsV	2	4	4	2	4	2	4	2	2.05
11	Quantity of cycles (strokes) of stamp machine per hole	PsV	2	4	2	2	4	2	4	2	1.02

Table 2 – Experiment factors and levels

Factor	Levels	Symbol	Description	Value	Unity
Rivet material	-1	AD	Alloy Al 2117	Al 2117	N/A
	1	E	Alloy Al 7050	Al 7050	N/A
Thickness of the package	-1	050	Thickness skin	0,050	inch
	1	080		0,080	inch
Gap before riveting process	-1	Fm	Minimum gap	0,09	mm
	1	FM	Maximum gap	0,24	mm
Type of riveting process	-1	M	Manual	N/A	N/A
	1	A	Automatic		
Countersunk height	-1	Am	Minimum height	Rivet 0,3	mm
	1	AM	Maximum height	Rivet aligned to skin	mm

To minimize the cost and the time of the experiment, two levels for each factor had been specified, using the existing variations in the aeronautical manufacture as shown in Tab. 2.

2.2. Accomplishment of the Experiment

The second stage of the work consisted of measuring several specimen obtained by the combinations of all the elected factors based upon the concepts of Design (or delineation) of Experiments and in Taguchi Orthogonal Arrangements (TAGUCHI, 1986). According to Logothetis (1989), three conditions must be satisfied for the execution of Design of Experiments: balance, estimate and orthogonal. It has been verified that the five factors met the orthogonal requirement, as they can be set separate and independently. Likewise, it has been verified that all the factors can have its effects estimated; thus the estimate requirement was also met. Then, it was necessary to elaborate a plan of experiments in which all the factors would be varied in the same frequency, that is, each combination of factors would have to be tested in the same amount of experiments, in order to meet the balance requirement.

To simulate the real assemblies, the specimen is composed of two plates that emulate the stringer, the skin and the yielded thicknesses with the usual assembly values (0,063 inches, 0,050 inches and 0,080 inches, respectively).

The pitch of riveting (2,5 cm) was chosen as the usual value for aeronautical structures, where the number of holes and rivets were calculated from. Figure 1 shows a schematic drawing of the designed specimen.

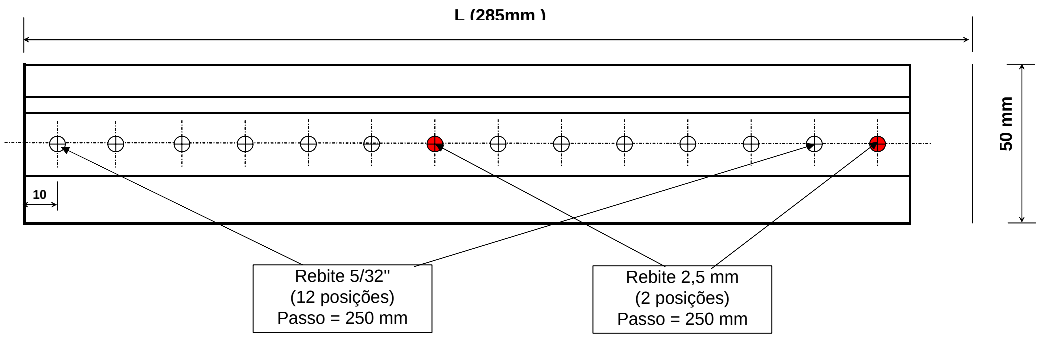

Figure 1 – Schematic drawing of the specimen

To fix the two plates to assembly the specimen, two holes with diameter of 2,5mm detailed in Fig.1 had been used for riveting two provisory rivets. Naturally, these holes and rivets had not been considered in the measurement of the expansion of the specimen.

As a dimensional expansion expected was around hundredth of millimeters, and the total length of the specimen is 285 mm, it was necessary to guarantee the perpendicularity between the faces. A special tooling was confectioned for this purpose. To get the necessary precision, the measurement procedure was performed using a dial gauge, whose accuracy is of hundredth of millimeters. For calibrate the dial gauge, it was confectioned a reference specimen identical to the experimental specimen. So, the reference probe was inserted in tool and the zero of dial gauge was established. This way, the dial gauge was calibrated at the beginning and during the execution of the experiment. After this, it was began the experiment with the experimental specimen. The dial gauge measures the distance between the specimens that is being measured in relation to the zero point of calibration. The bigger the expansion of the specimen, the lesser this distance and, likewise, the value measured for the dial gauge.

The initial and final values correspond to the specimen length values read by the probe before and after the riveting. The difference between these values is:

$$L = Li - Lf \quad (2)$$

where,

Lf: measurement of the specimen length after riveting

Li: measurement of the specimen length before riveting

To estimate the measurement uncertainty, two main sources had been considered: the uncertainty of the dial gauge and the thermal expansion of the plate as presented in Eq. 3.

$$eT = e_r + dtAl \quad (3)$$

where

eT: total measurement uncertainty [mm]

er = uncertainty of dial gauge = 0,005 mm according to the its technical specification.

$dtAl$: linear thermal expansion of aluminum [mm], as shown in Eq.4 (VAN VLACK, 1970).

$$dtAl = Lo * ct * \Delta t \quad (4)$$

where,

ct: thermal expansion coefficient of aluminum [ºC-1]

Δt: variation of temperature [ºC] and

Lo: initial length of the specimen (285mm).

In a controlled environment with variation of in the maximum 1ºC e ct = 23,8.10E-6/ºC (MATERIAL PROPERTY DATA, 2006), Equations (4) and (3) yields, respectively:

$dtAl = 285 * 23{,}8.10^{-6} * 1 = 0{,}006783$ mm

$eT = e_r + dtAl = 0{,}005 + 0{,}006783 \approx 0{,}01\text{mm}$

3. ANALYSIS OF DATA

The concepts of Analysis of Variance – ANAVA (DEVORE, 2004) have been used to analyzing the outcome data from the experiments as well as the software MINITAB™ version 14. The analysis of data was performed in three stages: Manual Riveting, Automatic Riveting and both. For each stage, the sequence shown in Fig. 2 was applied:

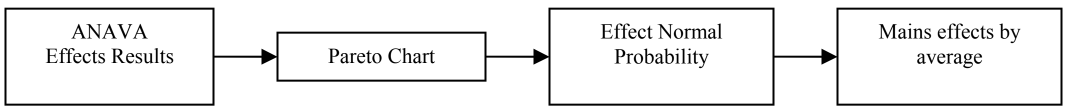

Figure 2 - Sequence of analysis of the data

In this paper, the analysis of the data of both - Automatic and Manual Riveting – is presented; the partial results of each of them are summarized in the Conclusions.

3.1. Manual e Automatic Riveting - TOTAL

Tables 3 and 4 present the results of the ANAVA and the effects and estimated coefficients for Total Riveting respectively.

Table 3 - ANAVA (Analysis of Variance) – Total

Sources	***df***	***SS***	***MS= SS/df***	***F***	***P***
Main effects	5	0,0250031	0,00500062	28,47	0,000
2X2 Combination	10	0,0087713	0,00087713	4,99	0,000
3X3 Combination	10	0,0056912	0,00056913	3,24	0,001
4X4 Combination	5	0,0028281	0,00056563	3,22	0,009
5X5 Combination	1	0,0000756	0,00007562	0,43	0,513
Error	128	0,0224800	0,00017562		
TSS	159	0,0648494			

Table 4 – Effects and Coefficients estimated – TOTAL

Term	***Effect***	***Coef***	***SE Coef***	***T***	***P***
Constant		0,030625	0,001039	29,47	0,000
Process	-0,008000	-0,004000	0,001039	-3,85	0,000
Material	-0,010000	-0,005000	0,001039	-4,81	0,000
Gap	0,004000	0,002000	0,001039	1,92	0,057
Thickness	-0,019000	-0,009500	0,001039	-9,14	0,000
Height	-0,009000	-0,004500	0,001039	-4,33	0,000
Process*Material	-0,008250	-0,004125	0,001039	-3,97	0,000
Process*Gap	0,005250	0,002625	0,001039	2,53	0,013
Process*Thickness	0,007250	0,003625	0,001039	3,49	0,001
Process*Height	0,005250	0,002625	0,001039	2,53	0,013
Material*Gap	0,002250	0,001125	0,001039	1,08	0,281
Material*Thickness	-0,003250	-0,001625	0,001039	-1,56	0,120
Material*Height	-0,001250	-0,000625	0,001039	-0,60	0,549

Gap*Thickness	-0,004250	-0,002125	0,001039	-2,04	0,043
Gap*Height	-0,001250	-0,000625	0,001039	-0,60	0,549
Thickness*Height	0,001250	0,000625	0,001039	0,60	0,549
Process*Material*Gap	-0,001500	-0,000750	0,001039	-0,72	0,472
Process*Material*Thickness	-0,002000	-0,001000	0,001039	-0,96	0,338
Process*Material*Height	0,004500	0,002250	0,001039	2,16	0,032
Process*Gap*Thickness	-0,004000	-0,002000	0,001039	-1,92	0,057
Process*Gap*Height	0,001500	0,000750	0,001039	0,72	0,472
Process*Thickness*Height	-0,004000	-0,002000	0,001039	-1,92	0,057
Material*Gap*Thickness	-0,002000	-0,001000	0,001039	-0,96	0,338
Material*Gap*Height	0,006000	0,003000	0,001039	2,89	0,005
Material*Thickness*Height	-0,002000	-0,001000	0,001039	-0,96	0,338
Gap*Thickness*Height	-0,006000	-0,003000	0,001039	-2,89	0,005
Process*Material*Gap*Thickness	-0,004250	-0,002125	0,001039	-2,04	0,043
Process*Material*Gap*Height	-0,006250	-0,003125	0,001039	-3,01	0,003
Process*Material*Thickness*Height	0,001750	0,000875	0,001039	0,84	0,401
Process*Gap*Thickness*Height	-0,000750	-0,000375	0,001039	-0,36	0,719
Material*Gap*Thickness*Height	0,003250	0,001625	0,001039	1,56	0,120
Process*Material*Gap*Thickness* Height	0,001500	0,000750	0,001039	0,72	0,472

3.1.1. Pareto Chart Analysis

The t (Student distribution) critical value was ≈ 1,979 for a level of significance α= 0,05 and degrees of freedom of the error equals to 128.

It can be noticed in Fig. 3, that all the combinations with values t (|T|) bigger than the critical value t, are significant. In a decreasing sequence of importance, they are: D - Thickness, B - Material, and E - Height, AB - Process and Material, A - Process, AD - Process and Thickness, ABCE - Process, Material, Gap and Height, BCE - Gap, Material and Height, CDE - Gap, Thickness and Height, AE - Process and Height and AC - Process and Gap. It is clear that the most significant factor by far is the thickness (D).

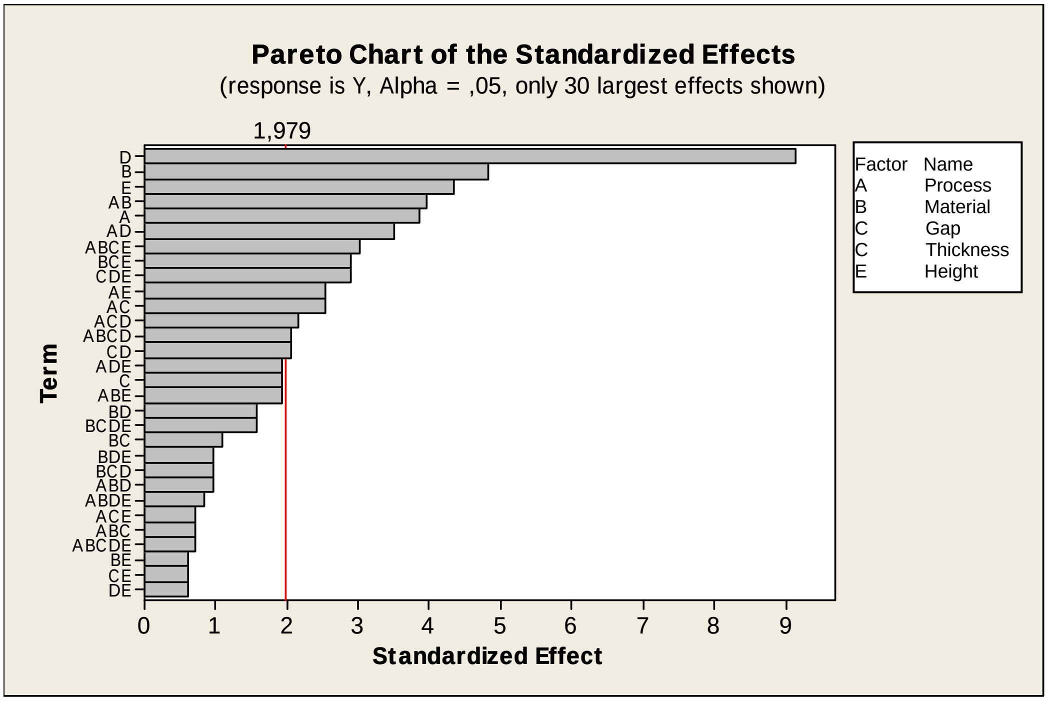

Figure 3 – Pareto Chart Analysis

3.1.2. Normal Probability Analysis

Figure 4 ratifies the findings of the Pareto plot illustrated in Fig. 3.
In a decreasing sequence of importance, the factors are: D – Thickness as the top effect down to AC - Process and Gap.

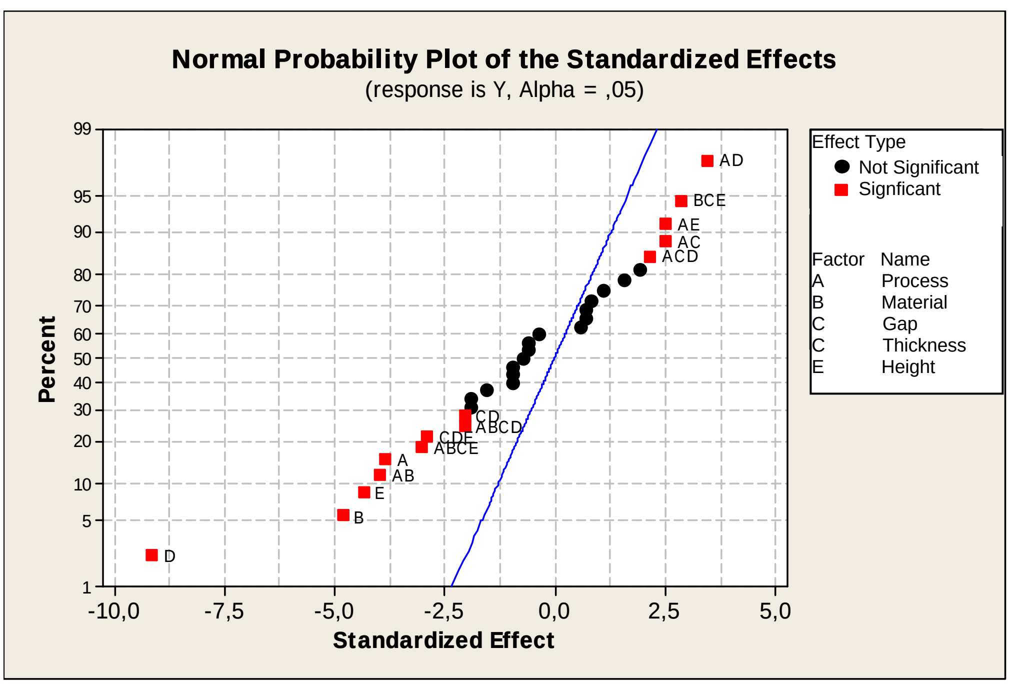

Figure 4 – Normal Probability Analysis

3.1.3. Average main effect

It can be verified in Fig. 5 and in Tab. 5 that the factors with bigger inclination – and consequently that causes more effect on the specimen behavior are: Thickness, Material, Process, Height and Gap coinciding with the previous analyses. However, according to analyses of Pareto and Normal, are significant only the Thickness, Material, Process and Height factor.

Table 5 – Variation Average per factor – TOTAL

Level	***Process***	***Material***	***Gap***	***Thickness***	***Height***
-1	0,03463	0,03563	0,02862	0,04013	0,03513
1	0,02663	0,02563	0,03263	0,02113	0,02613
Variation	0,00800	0,01000	0,00400	0,01900	0,00900
Position	4	2	5	1	3

The factor "Gap" was close to the $t_{critical} \approx 1,979$ (T = 1,92, see Tab. 4) but it has been considerer not significant for α=5%. However, it became significant in the combination with other factors due to the following hypothesis: the lesser the gap between the hole and the rivet, the lesser the thickness of the package and conversely, the lesser the countersunk, the bigger the deformation. This can be explained as a hypothesis as follows: a bigger amount of material of the rivet in the hole raises the pressure and expands the hole.

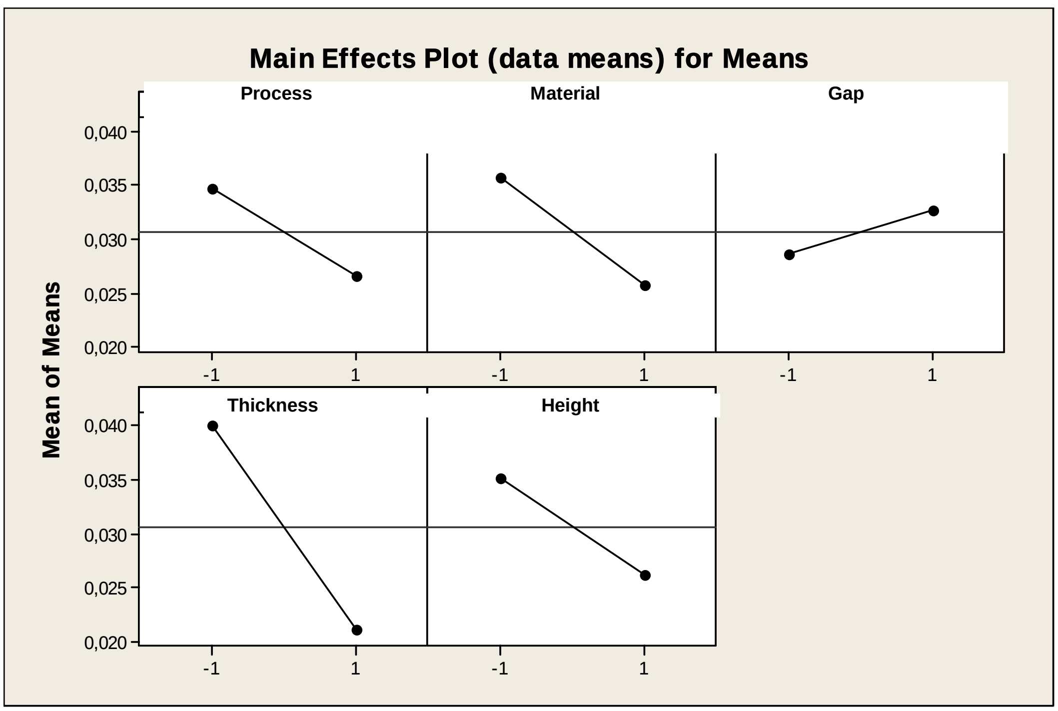

Figure 5 – Main effects per average - TOTAL

It was also observed that it has a significant variation between the Manual and Automatic Process between levels -1 and 1 for the deformation of the skin. However, the warping of the specimen observed in the Manual Riveting, has impaired any objective analysis and therefore, this affirmation cannot be proven. This occurs due to the interference of the operator in the application of the load of stamp machine and in the amount of cycles applied, causing (as in fact it occurred) a deformation in the superior face of the skin beyond the deformation caused for the expansion of the hole. Besides, the Automatic Process operates with only one cycle of riveting with constant application of the load that could cause better dislocation of the plate during the expansion generating lower plastic deformation. The biggest deformation observed in whole experiment was 0,07 mm on average of each combination for 12 rivets.

4. CONCLUSIONS

Table 6 presents the summary of each partial and total analysis and its respective significant factors. Analyzing the results presented in Tab. 6, one can conclude that the factor Thickness of the package is most relevant for the effect of expansion of the skin after Riveting, independently of the process, Manual or Automatic.

The biggest deformation observed in the Automatic Process was 0,07 mm on average of each combination. Considering the aircraft panels with riveting lines of 150 rivets, this would represent an expansion linear of 0,9 mm. As this expansion occurs but in the riveting line it induces warping and twisting in the panels, modifying the designed riveting line. Through a geometric calculation, the expansion of 1 mm would approximately cause the deformation in the aerodynamic system line of a panel with 150 rivets up to 2,4 cm.

It was observed in the Manual Riveting a warping bigger than in the Automatic Riveting, deteriorating the measurement system and consequently, the data of expansion for this process. However, the force used for the strokes (cycles) of the manual stamping machine directly in the skin is also attributed to this warping, causing a plastic deformation in the system line, adding up to the expansion of the hole.

As described in item 2, the main objective of the work was reached when the experimental analysis proved the effect of deformation in aluminum alloys skin when applied a determined riveting process. The secondary objectives of the work had been also attended because it had been identified between the factors selected (diameter of the hole, height of countersunk, material of the rivet, thickness of the skin and type of riveting - manual or automatic) those that influence, as well as the degree of this influence, in the deformation of the skin, summarized in Tab. 6.

Table 6 – Summary of the data analysis

Analysis	**Biggest expansion in 12 rivets**	**Significant factors α = 0,05**	**Level of the biggest effect**
Manual Riveting	0,05	A – Material C – Thickness B – Gap BCD – Gap, Thickness e Height ABC – Material, Gap e Thickness	- Type AD – smaller hardness - Smaller Thickness: 0,050 pol - Gap maximum
Automatic Riveting	0,07	C – Thickness D – Height ABD – Material, Gap e Height BC – Gap e Thickness	- Smaller Thickness: 0,050 pol - Height minimum
Total	0,07	D – Thickness B – Material E – Height AB – Proccess e Material A – Proccess AD – Proccess e Thickness ABCE – Proccess, Material, Gap e Height BCE – Gap, Material e Height CDE – Gap, Thickness e Height AE – Proccess e Height AC – Proccess e Gap	- Smaller Thickness: 0,050 pol - Type AD – smaller hardness - Height Minimum - Automatic Riveting Proccess

4.1. Possible alternatives to reduct the deformation effect

Aiming at minimizing the effect of induced deformation from the riveting process, it can be considered some actions in the process and product to vary the analysed factors. Some suggestions are presented with the recommendation that their implementation depend of further functional and financial analysis:

• Thicknesses of skin equal or superior to 0,080 pol;
• Height of countersunk in the maximum value allowed by standards as NASM 14219 (ANSI, 1999);
• Project of tooling to eliminate or minimize the stretching and the warping of the skin;
• Use of machined caves that guarantee the system line with the deformation of the skin.

4.2. Future developments

As opportunities for future developments of this work, it is suggested:

(i) the measurement to be made through photogrammetry or laser tracking, (LEICA, 2006), because with these devices, it is possible to obtain the linear measurement of the specimen, as well as the alteration in the line of system, that is, a curve of the product manufactured in relation to the projected curve in axes x, y and z.

(ii) to make experiments with other types of fasteners used in the aeronautical industry that such as: HI-LOK, HI-LITE, LOCK-BOLT (ALCOA, 2006), as well as other diameters of holes used with the Brille rivet or solid.

(iii) to analyze the effect of other factors namely the riveting sequence and the direction of the material grain of the plate.

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6. RESPONSIBILITY NOTICE