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SELF PIERCING RIVETING FOR METAL-POLYMER JOINTS

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ABSTRACT: Self-Piercing Riveting (SPR) is a sheet metal joining technique based on the insertion of a rivet into two or more sheets, with no preparatory hole. This process has gained wide diffusion in the automotive industry, due to the increasing use of materials alternative to steel, that are difficult or impossible to join with traditional techniques. In particular, polymeric materials are becoming increasingly used, due to their favorable weight/strength ratio. This paper reports the results of experimental investigations, aimed at identifying the variables affecting the mechanical characteristics of mixed metal-plastic joints. A statistic model for the optimization of the geometrical parameters has been computed. The paper demonstrates that self-piercing riveting appears competitive for metal/polymer junction. The results analyzed in light of statistical techniques show that some geometrical parameters affect joint performance more than others and can therefore be used as independent variables for joint performance optimization.

KEYWORDS: Sheet metal, Joining, Self Piercing Riveting, Mixed joints.

1 INTRODUCTION

The fabrication of lightweight products is a primary objective for most manufacturers. A well-known example is the automotive industry, where a reduction on the total vehicle weight of 10 % translates into a reduction of fuel-consumption and polluting emissions of around 8-10 %. A common practice is to manufacture lightweight products by using alternative materials However, a common limitation to these innovative materials are the joining methods, since spot-welding is impossible to apply to plastics and expensive and difficult to apply to metallic non ferrous alloys [1].

Among the alternative joining techniques for light-weight alloys and plastics, low cost and flexibility make Self-Piercing Riveting (SPR) one of the most promising [2]. Self-Piercing Riveting (SPR) is a fast and simple sheet metal joining technique based upon insertion of a rivet into two or more sheets, with no need for preparatory hole. It allows joining two or more sheets of different materials, with no smoke or heat emission and low noise. The authors are carrying out a systematic research activity on the subject, with the aim of filling up a general lack of knowledge that make SPR less widespread than its potentialities would allow [3].

In this paper an experimental campaign is presented, aimed at exploring the possibilities of joining together sheet metals and polymeric materials, in the attempt to relate the process variables to the performances of the joint. The experimental tests, carried out on 4 different plastic and 3 different metallic materials, shown SPR suitable for mixed joints. A statistical analysis shown that sheet thickness and tool design are the most important geometrical parameters affecting joint quality.

2 EXPERIMENTAL PROCEDURE

2.1 MATERIALS AND TOOLS

A single effect hydraulic riveting press produced by Textron Fastening Systems has been used to form the test samples. Punch and die were made of AISI 1045 steel. The rivets are made of Boron steel, with a composition very similar to AISI 94B30, coated by an 8 μm protective layer of a Zi-Pb-Al alloy, and were supplied by Textron. Four sizes of self-pierce rivets have been used, defined by stem and head diameter and height. Figure 3 shows the rivet geometries, while in Table 2 the numerical values of the dimensions are displayed. The dies are represented in Figure 4, while their dimensions are listed in Table 3.

The sheet materials used for this study are listed in the following. Other features are shown in Table 4.

1. Al2024-T3, an aluminum alloy reinforced by solid solution, and precipitation hardened (Al_2CuMg), with Cu = 4.2%;
2. FEP04, a low carbon steel (C = 0.08%), ductile and suitable for deep drawing;
3. Noryl GTX 924 ®, a thermoplastic produced from polyammide (nylon PA), reinforced with polyfenilene (PPE);
4. Xenoy CL 100 ®, a thermoplastic produced from poly(butylene terephthalate) (PBT) and polycarbonate (PC);
5. SMC, a fiberglass produced from unsaturated net-like polyesther with 30% glass fibers;
6. RTM, a thermohardening polymer composite, composed by 45% polyesther, 22% glass fibers and 30% calcium carbonate.

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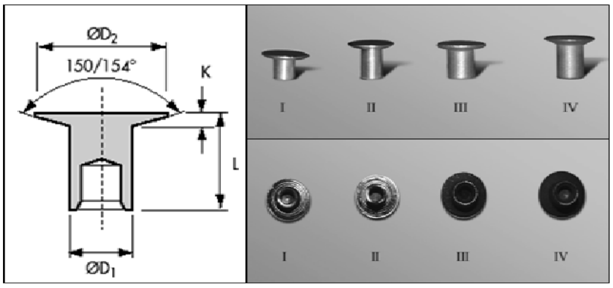

***Figure 3 :** Geometries of the rivet used for the experiments. Size are reported in table 2*

***Table 2 :** Dimensions of the different rivet sizes*

ø D1 (mm)	ø D2 (mm)	L (mm)	K (mm)	Code
3.9	8.0	4.1	1.2	I
3.9	8.0	5.8	1.2	II
4.8	8.5	5.8	1.5	III
4.8	8.5	6.7	1.5	IV

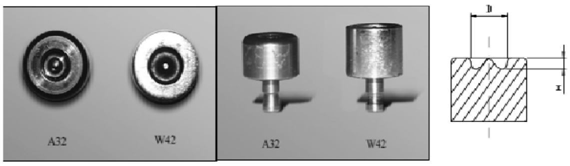

***Figure 4 :** Geometries of the dies*

***Table 3 :** Die sizes*

D (mm)	H (mm)	Code
7.4	0.80	A
8.0	1.75	W

***Table 4 :** Main features of the materials. 1) Al2024-T3, 2) FEP04, 3) Noryl GTX 924 ® , 4) Xenoy CL 100 ® , 5) SMC, 6) RTM*

	1	2	3	4	5	6
Volumic Mass (g/cm3)	2.77	7.85	1.09	1.22	1.91	1.55
Elastic Modulus (GPa)	73	210	2.1	2.2	13.1	2.7
Elongation at break. %	12	38	7.5	5	3	7.1
Max load (MPa)	198	280-300	55	55	90	79
Thickness (mm)	1 - 2	1	3	3	3	5

2.2 SHEAR TESTS

According to the internal norms of most automotive manufacturers, the test samples were formed by joining sheet rectangles of 100x25 mm. The rivet was positioned in the centre of the overlapping region, that had a square shape (see Figure 5). In the case of the metallic materials, the sheet metals were blanked keeping the main axis parallel to the cold-rolling direction.

Preliminary tests have been carried out to select the combinations of materials, thicknesses, dies and rivets of practical interest, based on the visual quality of the joint. Requirements were: rivet head leveled with the upper sheet, regular and uniform formation of the lower button, zero or low sheet metal distortion [4]. Since the lower sheet undergoes the highest deformation, the standard test combination saw the metallic sheets as lower sheets and the plastic as upper sheets. Figure 6 shows an example of the tests performed to find the correct joining force for Noryl GTX914® and Al2024-T3 – 1 mm.

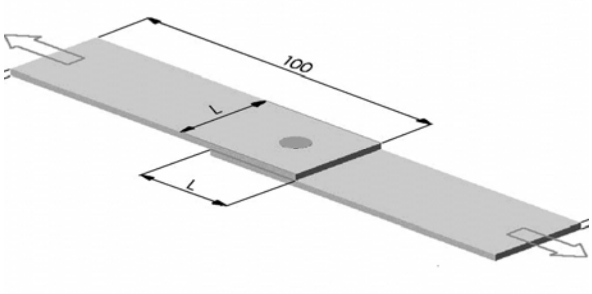

***Figure 5 :** Schematic diagram of the test sample*

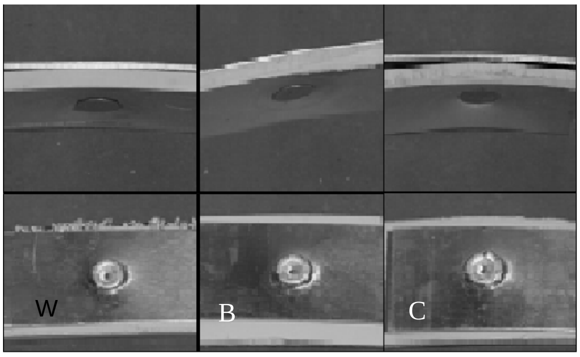

***Figure 6 :** Joints of Noryl GTX914® with AL2024-T3 – 1 mm, rivet iv, die w, variable joining forces. (A) protruding head, (B) even head, (C) sunk head.*

It can be seen that, from the point of view of the visual joint quality, a joining force of 24kN can be considered optimal. The preliminary tests indicated that the 4 polymeric materials could be successfully joined only by using rivets II, III and IV.

The shear tests have been carried out on a Universal testing machine Easydur MODEL 3MZ5. The tests have been performed with a constant speed of 2x10^{-3} mm/s, after the application of a pre-load of 10 N, and have been stopped at samples failure.

3 RESULTS AND DISCUSSIONS

The results of the joining tests have been at first selected on the basis of the visual quality. Selected combinations have then been subjected to shear tests. For each selected combination, 5 repetitions have been performed, in order to get information over the process dispersion. The final results of such experimental campaign are reported in Table 5.

***Table 5 :** Results of the experimental campaign. LS : lower sheet; US : upper sheet*

Combination (die-force-rivet)	LS (mater.-thick.)	US (mater.)	Head Position	Max. shear load (N)	Std. Dev. (N)
A 32 IV	1-1	5	1	1321	184
W 36 II	1-1	5	0 - 1	245	36
W 36 III	1-1	5	1	331	13
W 38 III	1-1	5	1	217	21
W 40 III	1-1	5	1	141	9
W 28 IV	1-1	5	0 – 1	1984	231
W 32 IV	1-1	5	0 - 1	2056	327
W 36 IV	1-1	5	0 - 1	1843	109
W 24 II	1-2	5	1	2786	172
W 28 II	1-2	5	1	2307	93
W 28 III	1-2	5	1-2	2059	281
W 24 II	2-1	5	1	1647	191
W 32 IV	2-1	5	1 - 2	1969	189
A 24 IV	1-1	3	1 - 2	1269	162
A 28 IV	1-1	3	1	1396	148
W 16 II	1-1	3	1	433	68
W 16 III	1-1	3	1	897	74
W 20 III	1-1	3	1	388	42
W 24 III	1-1	3	1	562	74
W 28 III	1-1	3	0 - 1	368	33
W 20 IV	1-1	3	1 - 2	1009	48
W 24 IV	1-1	3	1	2158	298
W 28 IV	1-1	3	1	1149	97
W 32 IV	1-1	3	1	1512	11
W 36 IV	1-1	3	1	1927	116
W 12 II	1-2	3	1 - 2	1983	175
W 16 II	1-2	3	1	2264	193
W 20 III	1-2	3	1	2461	360
W 24 IV	1-2	3	1	2306	116
A 24 IV	2-1	3	1	1950	284
W 20 III	2-1	3	1	863	108
W 24 III	2-1	3	1	1189	174
W 24 IV	2-1	3	1	2404	418
W 20 II	1-1	4	0 - 1	1826	212
W 20 III	1-1	4	1 – 2	476	50
W 22 III	1-1	4	1	405	30
W 24 IV	1-1	4	1 - 2	1768	46
W 26 IV	1-1	4	1 - 2	2025	182
W 12 II	1-2	4	1 - 2	1205	184
W 16 II	1-2	4	1	2091	269
W 20 IV	1-2	4	1 - 2	2009	193
W 24 IV	1-2	4	1	2191	198
W 20 II	2-1	4	1	1545	107
W 16 III	2-1	4	1 - 2	472	75
W 20 III	2-1	4	1	787	87
W 20 IV	2-1	4	1 - 2	2206	338
W 24 IV	2-1	4	1	2188	407

The combinations are designated with a code indicating the die, the riveting force (kN) and the rivet, i.e. A 32 IV stands for die A, riveting force 32 kN, rivet type IV. No valid joint with RTM 5 mm has been obtained, since they did not pass the first quality test. In Table 5, the results of the joining process are given in terms of head position, classified into “sunk” (2), “even” (1) and “jutting” (0), and in terms of max shear load and standard deviation. In order to be classified as “jutting” or “sunk” the rivet head must pass a measured axial distance from the sheet surface of more than 0.5 mm. In some cases, when the measurement was uncertain, an intermediate evaluation was given.

The load-stroke curve for each shear test has been recorded. In Figure 7 the load-stroke characteristics of the shear tests relevant to the Al2024-T3-2 with Xenoy are shown.

From a first observation of the results of the experimental tests, it can be concluded that the riveting force interval in which the best results can be obtained is included between 20 and 24 kN, while joints realised with Al2024 T3, with a sheet thickness of 2 mm, show the highest shear loads.

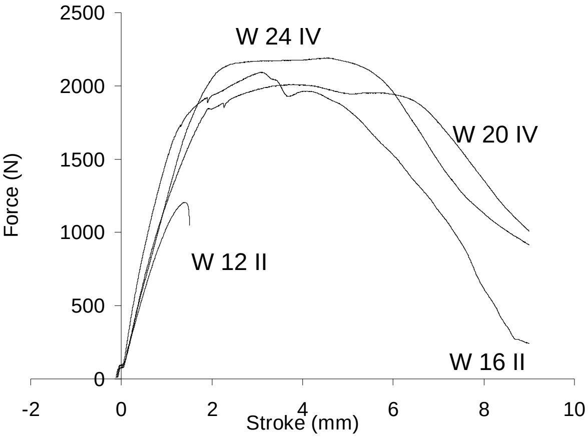

***Figure 7 :** Force – stroke characteristics for the combination AL2024-T3 – 2 mm with Xenoy, referred to the results shown in the table 5.*

3.1 REGRESSION ANALYSIS

A Multiple Regression Analysis has been performed to evaluate the shear strength of the joint vs. independent process variables such as die and rivet typology, riveting force, upper and lower sheet materials and thicknesses. A general model with interactions and second order effects has been computed by considering all the performed tests. The independent variables have been coded according to Tables 6 and 7. As for the rivet geometry, to individuate a single numerical variable in order to simplify the model, the diameter multiplied by the height has been chosen, as listed in Table 8. The results of the regression analysis, carried out with the stepwise method, are reported in Table 9.

***Table 6 :** Legend of the independent variables and their symbols.*

Variable	Symbol
Rivet	X_1
Die	X_2
Riveting Force	X_3
Plastic material	X_4
Metallic material	X_5

Table 7 : *Dummy variables used for the regression analysis*

Dummy Variables					
$X_2 = 1$	W die	$X_4 = 1$	SMC	$X_5 = 1$	Al 1 mm
$X_2 = 2$	A die	$X_4 = 2$	XENOY	$X_5 = 2$	Al 2 mm
		$X_4 = 3$	NORYL	$X_5 = 3$	FeP04

Table 8 : *Generation of the quantitative variable X_1*

Quantitative Variable X_1			
Rivet	Φ (mm)	h (mm)	$X_1 = \Phi \times h$
II	3.9	5.8	22.6
III	4.8	5.8	27.8
IV	4.8	6.7	32.2

Table 9 : *Results of the regression analysis. (F = 27.31253; F sign. = 0, 000001)*

Analysis of variance					
R	0.8971	ANOVA	df	SS	MS
R^2	0.8047	Regr.	4	28356963	3544620
Corr. R^2	0.7753	Resid.	57	6878340	129780.0
Obs.	62	Total	61	35235303	

The Corrected Square Regression coefficient of 0.7753 shows that the model accordance with the data is fair, and this is to be considered a good result, given the natural dispersion of the process.

The independent variables and parameters that showed effective in explaining the process behavior are: X_1 and X_1^2 (rivet geometry and its quadratic effect), X_3 and X_3^2 (riveting force and its quadratic effect), X_5 and X_5^2 (lower material and its quadratic effect), $X_1 \cdot X_3$ (interaction between rivet and riveting force), $X_2 \cdot X_3$ (interaction between die and riveting force), while die geometry (variable X_2) and upper material (variable X_4) did not prove significant in explaining the phenomenon.

The model equation is then the following:

$$\begin{gathered} Y = 17840.92 - 1686.85\, X_1 + 28.80\, X_1^2 + \\ 10.84\, X_3 - 0.03\, X_3^2 + 4655\, X_5 - 1094.25\, X_5^2 + \\ 0.49\, X_1 \cdot X_3 - 0.94\, X_2 \cdot X_3 \end{gathered} \tag{1}$$

This statistical model can be considered a tool able to give useful numerical indications on the most appropriate values of the process independent parameters to be chosen for the best joint performance, even if, as any statistical model, it is to be considered difficult to extrapolate to ranges of materials and parameters different from those explored.

A representation of a partial model extract from equation (1), for the case $X_2 = 1$ (die W) and $X_5 = 2$ (Al lower sheet, thickness 2 mm), is shown in Figure 8. Maximum strength is obtained with intermediate values of the riveting force (expressed in pressure units in the Figure) and for intermediate values of the rivet size. This means that, confirming what has been found in the riveting of more traditional couples of sheets, there exists a range of values inside which the riveting force must be kept in order to obtain an effective joint [5].

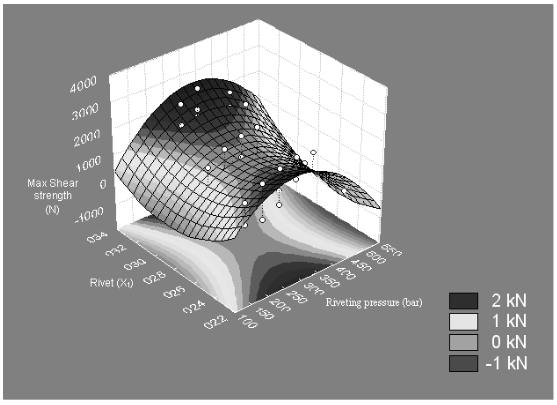

Figure 8 : *Representation of the statistical model of shear joint strength vs. river type and riveting force, in the case of x2 = 1, x5 = 2*

4 CONCLUSIONS

In general, it can be stated that self-piercing riveting appears competitive for metal/polymer junction.

It has been demonstrated that the process depends strongly on the geometrical parameters of the rivet, on the riveting force and on the metallic material, which should always be placed on the bottom side of the joint, i.e. the die side, since it is more deformable.

The aesthetic quality of the joint (even head, regular button, low material distortion) is a primary index of good joint strength, even if a visual test is not enough to assess the joint performance.

The statistical model defined on the basis of the experimental tests is a tool able to give useful indications over the most suitable values of the design parameters, and can be considered a first reference to orientate the designer.

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