MANUFACTURING PROCESS OPTIMIZATION FOR COMPOSITE-STEEL MULTIMATERIALS DESIGN

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Abstract

The present work deals with different aspects of the manufacturing process optimization of thermoset composites- steel components, on the grounds of process speed, and joint resistance. A range of composite prepreg systems, and innovative surface treatments had been considered in this study so to ensure the optimum performance of the solution for automotive components. Special emphasis was placed on the dissimilar composite- steel adhesive joint strength evaluation, together with its dynamic performance under impact. A range of strategies had been assessed to avoid galvanic coupling while maximizing the adhesive strength. The influence of innovative processes such as laser surface texturing had also been considered and the effect of the most significant operational parameters had been quantified.

Finally, it was possible to optimize and identify the optimum manufacturing parameters. Process speeds as low as 90 seconds show promising results reaching joint shear strengths up to 19MPa by using matrix enriched prepregs. Also, prepreg systems under study has shown prominent results on a variety of surface finishes attaining 15MPa with the simplest surface treatments. This proves high potential for the co-cured multimaterial components development by press forming for automotive industry.

1. Introduction

The concept of multi-material design has emerged in recent years to address constraints of cost, performance and weight, among others. The basic principle is simple, materials of different nature are combined in the same structure, so that the optimum material is used for each purpose attaining a higher cost/performance ratio than the respective bulk materials individually. Thus a unique solution fit for the purpose is attained as a result at a rationalised cost. In this sense, multi-material structures formed by a combination of polymer- based composites and metallic materials (mainly steel) are capturing a special interest in industry, especially due to the freedom of design and versatile nature that the composite counterpart confers. At present, many conventional composite manufacturing processes are being explored so to develop efficient multimaterial fabrication routes. This implies not only to develop a fully consolidated composite part, both thermoset and to a lesser extent thermoplastic, but also to develop a fully operational dissimilar joint (i.e. co-cured multimaterial components). As an example it should be highlighted recent studies on ATL/AFP manufacturing [1-4], thermoforming [5], injection molding [6], filament winding [7], etc. aimed to fully explore their potential for multimaterial manufacturing by developing the technology adequately. The later certainly implies attaining a high performance dissimilar joint for which in many cases, depending on the specific materials and grades involved, will imply implementing additional steps regarding surface

treatments. On the other hand another research trend that should be mentioned is the recent developments in fast curing resins which exhibit high promise for high production rates industries and, particularly for the automotive sector.
This study addresses both aspects by studing conventional and fast curing resins and its potential for developing multimaterial components for the automotive sector. Thus, different surface treatments and processing conditions had been analysed in order to quantify and identify the most suitable processing route in term of performance, processing speed and cost.

2. Experimental Procedure

2.1 Materials

The present work deals with the multimaterial development concept applied onto a high strength cold rolled steel typical of some automotive applications. Thus, a martensitic steel 1,6mm thick with a yield point of 1200-1500MPa and maximum resistance of 1470-1700MPa has been used throughout the present investigation. Regarding the polymeric counterpart three different carbon fiber thermoset prepreg systems had been applied (CFRP). In this case epoxy systems had been selected due to their excellent mechanical properties and high environmental resistance. Also, the outstanding adhesion properties of this resin family makes them one of the most suitable candidates for co-cured multimaterial applications. Currently there is a considerable range of epoxy prepreg systems commercially available, however high T_g and processing rate have been priorized as selection criteria. The CFRP used together with their main properties are included in Table 1. It should be mentioned that System A corresponds to a prepreg grade extensively used in several industrial sectors establishing, in this manner, a baseline level for comparison purposes.

Table 1. CFRP thermosetting prepreg systems under study.(* recommended on TDS)

Reference	Processing cycle*			Requirements
	t (min)	T (°C)	P (bar)	Tg (°C)
System A	90	125	7	110
System B	10	130	5	135
System C	15	140	10	192

2.2 Manufacturing process

In the present investigation press forming has been used to develop a one-shot process able to achieve the dissimilar joint development together with a fully consolidated composite part, in other words, a co-cured multimaterial component. In order to do so the different manufacturing stages had been thoroughly analysed independently. Thus the process window has been studied, firstly, by manufacturing monolithic composites followed by manufacturing the co-cured multimaterial specimens.

Preliminary trials targeted the comparison of the three different systems. Thus, the TDS recommended processing cycles where used for each specific system in both the monolithic and the multimaterial components. This allowed to identify the different behaviour of the different materials. Once this was accomplished the process window was adjusted for the best prepreg system where the processing parameters were varied. Mainly, the processing time had been tweaked and, hence, the temperature in order to reach higher productivity rates. The press trials were perfomed using a LabPro 1000, hydraylic platen press from Fontijne Presses & Services BV.

The performance had been assessed in terms of mechanical properties, and quality analysis had also been undertaken assessing the void content, degree of cure, etc. The tensile strength was characterized by following ASTM D3039, the bond strength was determined by perfoming single lap joint tests (ASTM D5868) and an impact test was used for comparative purposes. Regarding the latter the lack of standards related to the impact assesment of hybrid structures had driven the alteration of the dimensions and manner of applying the impact. In any case a universal charpy pendulum was used and the metallic standard (ISO 148) and composite standards (ISO 179 and ASTM D6110) were taken into consideration. In impact testing a notched specimen is commonly used since in this manner complete fracture is ensured and a more stable crack propagation is normally guaranteed leading in this manner to a more robust testing procedure. Even so, in this case due to the particularity of the study cases and more specifically its dimensions where the low thickness of the steel limits the possibily of machining the notched, it was determined to use unnotched specimens. Also, indications of ISO 179 were borne in mind, by studing the influence of directionality of the stacking sequence into play.

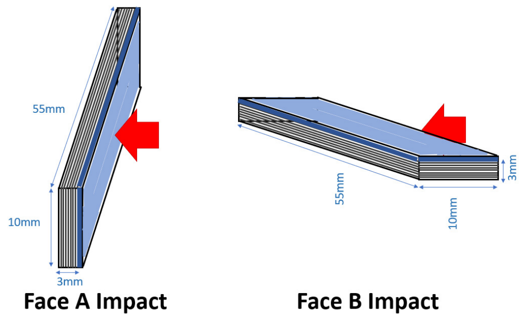


Figure 1. Schematic of the impact test performed on the multimaterial components where the orientation of the sample related to the impactor is displayed. The red arrow stands for the the impactor, whereas blue indicates the AHSS steel and the stacking sequence is represented in grey.

2.3 Surface treatments

Joint strenght is a critical requirement for a multimaterial component and, as such, it has been analysed in detail. Standard treatments have been considered following ISO17212 namely, cleaning (C), grit blasting (GB) and, finally, more innovative treatments like laser texturing (LT). In this case grit blasting has been performed by following a previously optimized treatment for CFRP-steel dissimilar joints [8]. Metallic angular grit form A.m.p.e.r.e had been applied with a pulsar III cabinet from CLEMCO. Laser texturing has experienced in the last years an increasing interest in many industrial fields. In the specific case of steel-composite adhesive joints and multi-material design, the state of development is at its earliest stages, as long as the most suitable structures for each combination of materials and/or for different purposes are not known exactly. In any case, and although the number of publications and research in this last field is beginning to grow [9-19], it is still necessary to carry out a complete investigation in order to identify the most appropriate structure for each material and each application. In this case the surface texturing of the base material was carried out by means of an ablative process since it is relatively non-invasive preventing, in this manner, the substrate from being thermally affected. The equipment used to carry out surface texturing has been a pulsed nanosecond laser (ns) Power Line E20 from ROFIN. In particular, a Nd: YVO4 laser has been used, with pulses between 10 - 20 ns and a fundamental wavelength of 1064 nm. The laser equipment has been combined with a flat field lens and 100mm focal length, together with a galvanometric scanner head that allows the laser radiation to be directed towards the substrate at rest and perform complex structures at reasonably high speed. After performing the analysis of the laser pulse footprint on the substrate under study the laser pattern was defined. The latter was done according to previous investigations [19-20]. The scanning strategy consists in the realization of a series of vertical lines, with a low degree of overlap between pulses. These lines are repeated a total of 15 times, with a displacement distance of 6 µm. In this way, it is possible to generate a periodic structure of riblets with a greater roughness in the bottom of the channels generated and a greater peak-valley difference. Once the 15 repetitions are made, in the same plane Z, the process is repeated in a new plane (Z') = (Z) - ΔZ, with ΔZ = 0.05 mm seeking a depth increase of the microtexture. The following figure shows a diagram of the scanning strategy used.

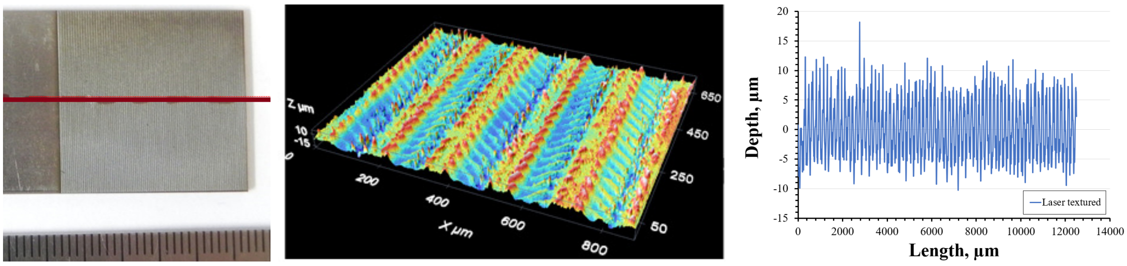


Figure 2. (from left to right) picture of a textured surface, 3D confocal maps and 2D profile obtained by means of a contact profiler.

Finally several additonal surface strategies have been considered so to ensure avoidance of galvanic coupling phenomena. In the framework of the investigation the effect of those on the joint strength has been assesed. In this sense it should be noted that galvanic coupling is one of the barriers to be solved in the multi-material design based on combinations of steel and carbon fiber composites. Both materials, due to their different electrochemical potential, when they come into contact with an electrolyte form a galvanic cell in which the anode (more negative potential) undergoes corrosion. In addition, the greater the difference in charge, the faster the corrosion of the more electronegative material. In any case, it is a phenomena that can compromise the structural integrity of the component as a whole, therefore it is fundamental to guarantee the electrical isolation between both counterparts. This can be done by ensuring that the matrix of the polymeric composite provides a highly controlled and homogeneous thickness to avoid contact, which is quite complicated especially taking into account the dimensional tolerances of the automotive sector. Alternatively it could be achieved by auxiliary means, that is, fiberglass fabrics of greater or lesser GSM (grammage), fiberglass mats, adhesives, etc. In this particular case, fiberglass prepreg (GF) and matrix enriched (ME) carbon fiber prepreg have been used. The experiments performed are summarized in Table 2.

Table 2. Main parameters and variables studied in the framework of the present investigation.

Component	Steel	Composite	Surface strategy	Processing cycle				Reference
				#	t/min	T/°C	P/bar	
MONOLITHIC	-	System A	-	1	90	125	7	A(1)
	-	System B	-	1	10	130	5	B(1)
	-	System B	-	2	7	120	5	B(2)
	-	System B	-	3	1.5	160	5	B(3)
	-	System C	-	1	15	140	10	C(1)
MULTI-MATERIAL	AHSS	System A	GB	1	90	125	7	A(1)-GB
	AHSS	System A	LT	1	90	125	7	A(1)-LT
	AHSS	System B	C	1	10	130	5	B(1)-C
	AHSS	System B	GB	1	10	130	5	B(1)-GB
	AHSS	System B	LT	1	10	130	5	B(1)-LT
	AHSS	System B	GB+GF	1	10	130	5	B(1)-GB+GF

AHSS	System B	GB+ME	1	10	130	5	B(1)-LT+ME
AHSS	System B	GB	2	7	120	5	B(2)-GB
AHSS	System B	GB	3	1.5	160	5	B(3)-GB
AHSS	System C	GB	1	15	140	10	C(1)-GB
AHSS	System C	LT	1	15	140	10	C(1)-LT

3. Results and disscussion

3.1 Behaviour of different epoxy systems

The analysis of the tests perfomed with the recommended manufacturing process parameters lead to mechanical results in agreement with which it was expected for the monolithic materials. In the case of the single lap joints the influence of grit blasting and laser texturing was analysed leading to different effectiveness depending on the specific grade. As it was explained the principles behind laser texturing, similarly to adhesive bonding, are not completly understood for these particular applications. At present there are many theories that try to explain the effectiveness of each surface finish for each specific system but unfortunatly none of them is yet completely satisfactory. At the moment, its tunning and selection has to be done with a trial and error iterative procedure. The main fundamental models able to explain the mechanical behavior of some of these dissimilar joints are the following; mechanical model, weak boundary layers model and additional factors such as wettability and surface energy. Being, in most of the cases, the first one considereded as the dominant one. Also additional factors will need to be carefully analysed mostly related with the physical properties of the resin (viscosity, volume, etc.) and its relation with the processing conditions which could certainly influence the joint strength and in some cases could lead to defects such as voids and lack of material, among others. Figure 3 shows the results together with some of the test performed to analyse the data. Laser texturing leads to an increase of contact area of approximately 11% compared to the modest 4% that grit blasting can achieve. Also the parameter Rz normally considered of utmost importance in both adhesive bonding and paint applications is improved by 400% while grit blasted achieves 250%. As it can be seen this is not directly translated on the mechanical strengths attained. Thus, laser texturing improves the resistance by 70% and 30% for System A and System B, respectively. While System B remains virtually the same. The optical inspections performed by means of optical microscopy were not able to identiy any clear difference among systems in terms of defects on the overall structure and, particularly, on the steel/composite interface. Also surface energy was determined according to UNE-EN 828 and very similar values were obtained for the three systems (i.e. 38-48 mN/m) that, on the other hand, were consistent with epoxy family values. All the above corroborates that there is not a clear explanation for the results attained in the three different systems and, as it was previously stated, the strategies to maximize joint strength will need to be developed on the one to one basis. Finally it should be mention that in both fast curing systems the joint strength obtained are superior to the obtained with the traditional system evaluated (i.e. 8MPa). This justifies the potential of fast curing resins for one-shot process development without the need of an adhesive.

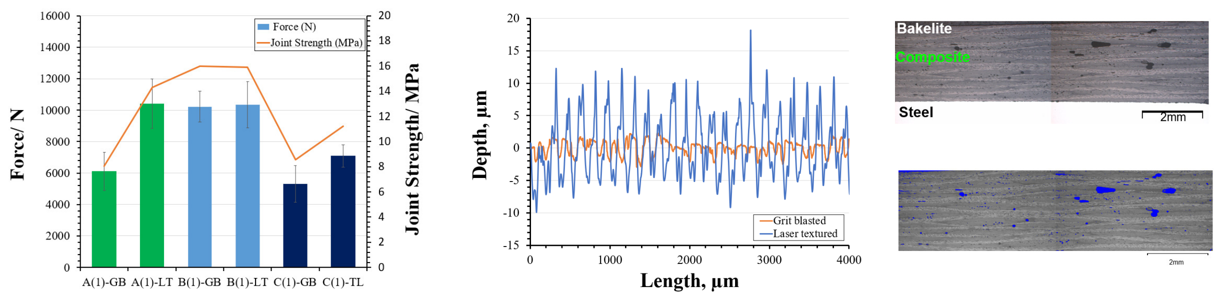


Figure 3. (from left to right) shear strength of single lap joints, 2D profile for grit blasted and laser textured surfaces, and cross section of the joints manufactured including porosity quantification.

3.2 Process window optimization

The study was completed by examining several process variables applied just on system B, since it clearly outperformed system C. Figure 4 displays the results attained, and the aforementioned additional verifications were performed in order to further anaylse the data. It can be seen that System B leads to high values even with the simplest surface preparation method (i.e. B(1)-C). Thus, just cleaning the steel surface leads to values up to 15MPa. However it should be highlighted the high scatter of those results, which is consistent with this preparation method (i.e. manual, mild, etc). The highest value has been achieved with the matrix enriched prepreg placed on the surface where 19MPa have been attained.

The different process speeds under study have shown minor variations on the joint strength of the single lap joints. Those results where also correlated with the degree of cure, tensile strength in direction 1 (0°) and porosity (cycle 1; degree of cure: 88,58%, χ:768 MPa, porosity; 5-7%/ cycle 2; degree of cure: 94,85%, χ:731 MPa, porosity; 8%/ cycle 3; degree of cure: 86,07%, χ:732 MPa, porosity; 10%). The values obtained indicate that the process speed could be reduced down to 90 seconds.

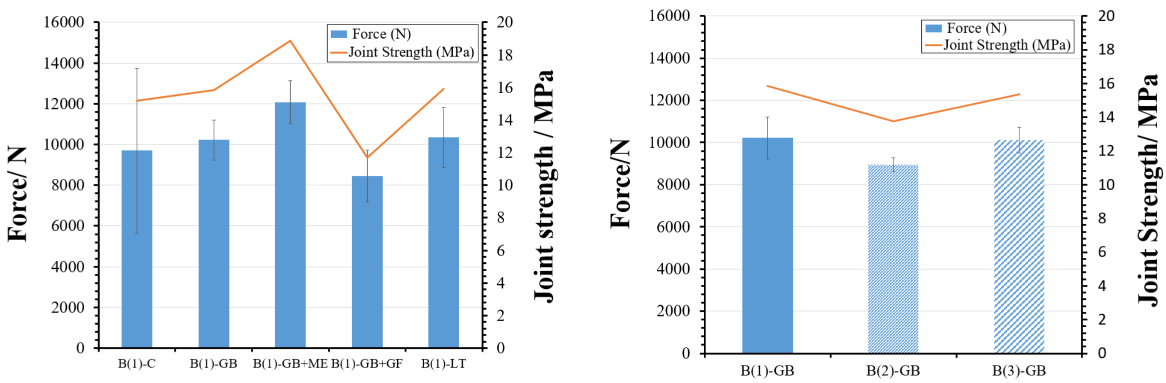


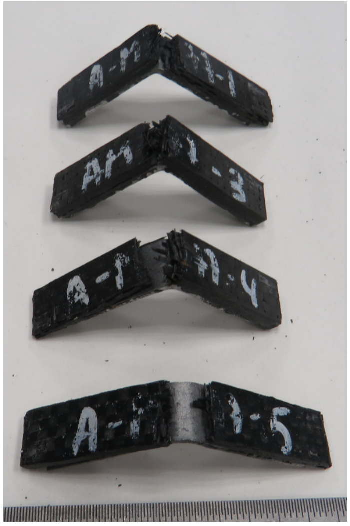
Figure 4. shear strength of single lap joints of system B (left) with different surface conditions and (right) different processing cycles.

3.3 Impact resistance

Table 3 displays the energy absorption attained in each of the systems under study. It should be noted that during the testing set-up a range of multimaterial components where tested and a correlation with the joint strength obtained by means of static testing seems to occur. However, as it can be seen here, B(1)-GB and C(1)-GB led to quite similar results despite the difference on joint strength previously displayed (Figure 3). Also, the results reveal energy absorption values for both monolithic composites quite similar, in this point it should be noted that those are in the lower range of the testing equipment. Impacts performed on face A of the multimaterial components lead to higher values related to their parent components. Further analysis is still ongoing in order to develop a deep understanding of both the test and the multimaterial components.

Table 3. Impact results for monolithic and multimaterial samples including the enery absorption values as a function of the orientation of the impact. Also, the failure mechanism for B(1)- GB is included.

	Monolithic		E, J	Multi material		E, J
Face A	Steel	Average	14.6	-	Average	-
		SD	*0.8944*	-	SD	-
	B(1)	Average	3	B(1)-GB	Average	21.00
		SD	*0.0100*		SD	*0.71*
	C(1)	Average	2.25	C(1)-GB	Average	18.40
		SD	*0.5000*		SD	*0.89*
Face B	Steel	Average	47.4	-	Average	-
		SD	*2.1909*	-	SD	-
	B(1)	Average	3.6	B(1)-GB	Average	35.40
		SD	*0.5477*		SD	*8.17*
	C(1)	Average	2.75	C(1)-GB	Average	34.80
		SD	*0.5000*		SD	*5.36*



4. Conclusions

Fast curing resins have proven to have great potential for one-shot process development for multimaterial design (i.e. without the need of an adhesive). Process speeds as low as 90 seconds lead to satisfactory results well above 12MPa, which is the threshold commonly considered for structural adhesive joints. The results obtained with the different systems and different surface strategies reiterates the need of developing the strategies to maximize joint strength on the one to one basis

Acknowledgments

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