Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 55 (2016) 59 – 64

www.elsevier.com/locate/procedia

5th CIRP Global Web Conference Research and Innovation for Future Production

Unified approach in design and manufacturing optimization of hybrid metal-composites parts

Panagis Foteinopoulos[a] , Panagiotis Stavropoulos[a, b], Alexios Papacharalampopoulos[a], George Chryssolouris[a, *]

[a]Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Patras 26500, Greece
[b]Department of Aeronautical Studies, Hellenic Air Force Academy, Dekelia Air-Force Base, TGA 1010 Athens, Greece

* Corresponding author. Tel.: +30-2610997262; fax: +30-261 0997744. E-mail address: xrisol@mech.upatras.gr

---

Abstract

An optimization strategy is described herein for the design and manufacturing of parts, combining composites and metals. The design stages of such parts, as well as the modelling procedures, required in each stage, are presented. More specifically, the modelling steps that are essential for the optimization of the production processes are described. A sample analysis of three different parts is also included. Moreover, a strategy for the optimization of the process parameters is proposed. This is based on maximizing the Key Performance Indicators (KPIs) of each process, considering the difference in the importance of each factor, between the different industry sectors. Finally, issues such as humidity and size effects are also taken into account

Keywords: Composites manufacturing; Decision making; Simulation of processes; Design for manufacturing; Optimization; Hybrid parts

---

1. Introduction

The combination of metal parts with composites lead to hybrid parts with a lot of advantages: Such parts have better specific properties than those of the fully metal parts, due to their composite part, whereas, they minimize the common disadvantages of fully composite parts (anisotropy, compression-dominance), due to their metal component. Subsequently, the metal-composite hybrid parts combine the advantages of two material types, simultaneously minimizing their disadvantages.

Up to now, the problems that manufacturing was faced with, when dealing with this kind of parts, were both the dissimilar material joining and the manufacturing of the composite part, relatively fast and at a low cost. However, recent advances made in automated tape placement, have rendered possible the fully automated manufacturing of composites, with optimized mechanical properties [1], [2]. Moreover, such automated processes are characterized by fast production rates, since there is no need for autoclave curing. The use of thermoplastic-based composites has led to better mechanical properties than those of the previously used thermosets, as well to more environmentally friendly composites, due to the recycling capabilities of the thermoplastic matrix.

As far as dissimilar joining is concerned, there are numerous alternative options such as bolting, screwing, riveting, welding, adhesives joining, or a combination of the those [3], [4]. Each method has different advantages and disadvantages, however, in this approach, the joining with the use of a thermoplastic adhesive layer will be analyzed, because of its low price and weight and other advantages namely, the fact that it uniformly distributes the mechanical loads Furthermore, fewer components are required in order for the joining to take place than it does in other methods and it leads to rigid, sealed and isolated unions [5]. Such joining methods significantly contribute to increasing further the process automation, as it can be incorporated into the

doi:10.1016/j.procir.2016.09.035

automated tape placement procedure, which will also offer the thermal energy necessary for the potential curing. Finally, the use of thermoplastic adhesives enables the disassembly; whereas, the thermosets adhesives have rendered the connection permanent by making the disassembly process impossible.

Subsequently, both the problem of the production rates and the cost, as well as that of the joining between those two materials have been tackled with constituting the metal-composite hybrid parts as a viable choice, with many advantages.

The current study sets the boundaries of a methodology that has to be followed during the design of such hybrid parts. The decision making strategy, along with the three aspects of modelling (i.e. Part design, texturing/joining design and Lay-up optimization) necessary for the successful design of such a part, have been analyzed in depth.

2. Decision Making Strategy

In order to successfully design and manufacture a hybrid part, the steps to be followed can be seen in Figure 1. Initially, the determination of the geometry and functional specifications [6] has to be conducted. More specifically, the geometry specifications and the part's ability to properly work /withstand the loads of its excessive working conditions are the goals that the design process has to meet. Utilizing this information, and also taking cost and desired weight into account, the material selection will be conducted: the type of the metal and the composite to be used, as well as the percentages of both will be defined, taking the desired weight into account [7], as well as the cost and manufacturing time restrictions. This will lead to the important design decision, concerning the percentage of load the composite will receive, which will determine the necessary number of plies and their orientation. This procedure may well be carried out in a reversed way, depending on which goal is the most crucial-difficult to satisfy (weight, cost, specific material that has to be used). Other types of loads, such as thermal and humidity, except for the mechanical ones, have to be taken into account in the material's selection.

Moreover, the part, according to its use, may have to be tested both in normal repetitive working condition loads (fatigue test), as well as in emergency excessive loads (strength test) [6]. All the above selections will have to be tested via simulations. The joining between the materials can be considered ideal for this stage.

The second step, as it can be seen in Figure 1, for the optimization of the design of the hybrid metal-composite part, is the selection of the joining type of the two subparts (metal and composite). In order for this to be done, the operational environment conditions such as humidity, temperature and vibrations, have to be taken into account, since they play a major role in the deterioration of the joining [7]. This selection has to be tested through simulation, which will take into consideration the joining characteristics. The results of the simulation will help in the validation or rejection of the type of the joining selection.

The final step is the optimization of the lay-up process, for the manufacturing of a part with the best possible quality characteristics (manufacturing (MFG) related KPIs). The optimal process parameters of the lay-up process have to be chosen (velocity of the head, heating power, consolidation force). This selection will be made by creating a simulation of the lay-up process which will enable the part's quality assessment using different process parameters, as well as the calculation of the manufacturing time required.

3. Modelling

3.1. Part Design

In this step, a simulation of the part to be manufactured is required for the validation of the design's capability to bear the specified loads. The weight of the structure will be also calculated. In order for this to be achieved, three different designs have been analyzed. All parts have a cylindrical cross section and low thickness. The first, is a fully dense metal

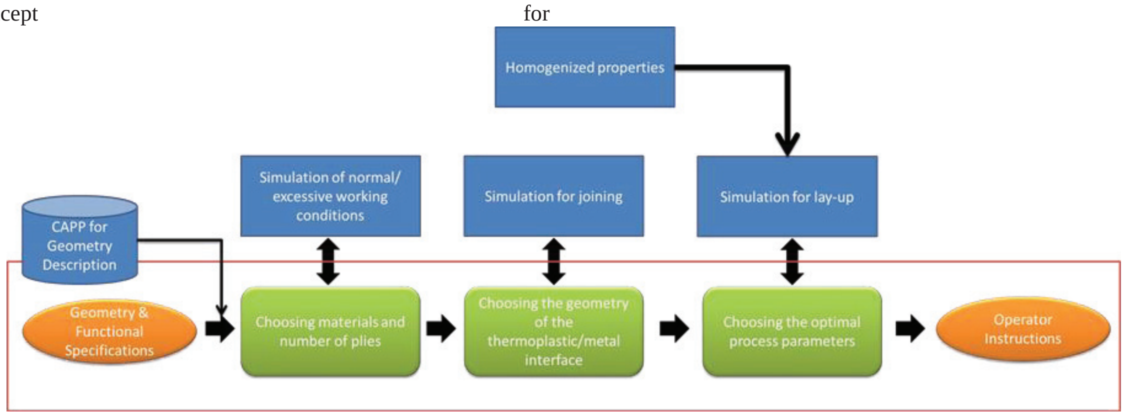

Figure 1 Design decision making strategy framework

Table 1 Material Properties

Property	Steel	IMA-12K	EPO-TEK 301-2
Density $[kg/m^3]$	7850	1580	998
Young’s Modulus (x direction) *[GPa]*	200	178	3.66
Young’s Modulus (y direction) *[GPa]*	200	9	3.66
Poisson Ratio	0.3	0.27	0.358
Shear Modulus *[GPa]*	76.9	5.2	1.35
Tensile Strength (x direction) *[MPa]*	250	3050	25.86
Tensile Strength (y direction) *[MPa]*	250	80	25.86
Compressive Strength (x direction) *[MPa]*	250	1500	
Compressive Strength (y direction) *[MPa]*	250	250	
Shear Strength *[MPa]*	145	94	

part, the second, is a hybrid metal composite part, of equal thickness to that of the fully metal one and the third is also a hybrid metal-composite part, thicker than previous stated option, but still lighter than the fully metallic one. The designs of the fully metallic and the hybrid parts can be seen in Figure 2 and their properties in Table 2.

Table 2 Design Properties

	Fully Metal	**Hybrid 1**	**Hybrid 2**
Inner Radius	10 mm		
Outer Radius	55 mm		
Thickness	10.2 mm	10.2 mm	31.7mm
Weight	0.81 kg	0.45 kg	0.75 kg
Thickness of Metal	10.2mm	5mm	5mm

The lay-up of the parts is Quasi-isotropic [9] (Figure 3), with the second design having more layers than the first. The materials that have been used are Structural Steel (metal), the composite is IMA-12K [10], which is a toughened epoxy resin system supplied with unidirectional carbon fibers and the adhesive is EPO-TEK 301-2 [11], which is a two component optical, medical and semiconductor grade epoxy resin. The properties of the materials that have been used can be seen in Table 1. For the hybrid parts, the layers of the composite have been added on both sides of a thin metal core.

3.1.1 Static and Dynamic Analysis

Static and dynamic analyses have been conducted for the evaluation of the mechanical properties of the three different designs. The interface between the different components of the hybrid parts has been considered as “fully bonded”. The parts have been loaded with a moment of 500 Nm in their outer profile. A fixed support has been used in their inner profile. The load and the support can be seen in Figure 4. The results of the static analysis (deformation distribution) can be seen in Table 3 and in Figure 2 (left).

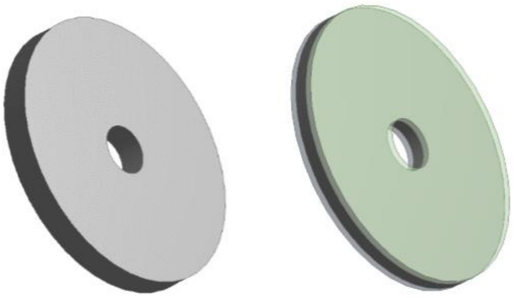

Figure 2 Fully metal (left) and hybrid metal-composite (right) designs

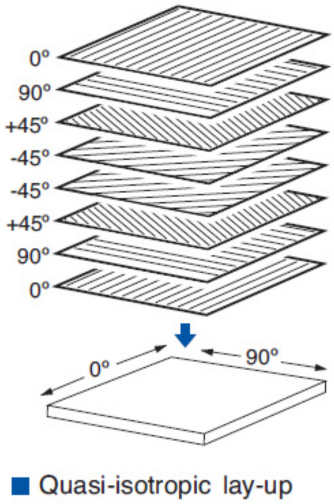

Figure 3 Quasi-isotropic lay-up [8]

Furthermore, the dynamic behaviour of the three parts has been tested. Modal analysis has been conducted, using the same support to the static analysis. The results can be seen in Table 4 and in Figure 5 (right).

As it can be observed, the same load causes a greater deformation to a hybrid part than to a fully metallic (steel) one of the same thickness. Also, its first mode of resonance is at a lower frequency than that of the steel part of the same thickness. However, if more layers, which will lead to a thicker part, but still lighter than the metallic one, are added to the hybrid part, , its mechanical properties, both the static (less deformation) and the dynamic (higher fist mode) are better compared with those of the metallic one.

Table 3 Static analysis properties and results

	Fully Metal	**Hybrid 1**	**Hybrid 2**
Support	Fixed Inner Profile		
Load	Outer Profile: Moment of 500 *Nm*		
Deformation	$2.442\ 10^{-5}$ m	$4.415\ 10^{-5}$ m	$2.764\ 10^{-5}$ m

In addition, a high and low cycle fatigue test should be conducted in order to determine the maximum life of the hybrid parts, which should be compared with that of the fully metallic part. Finally, some composite specific tests should also be conducted [12].

Table 4 Modal analysis properties and results

	Fully Metal	**Hybrid 1**	**Hybrid 2**
Support	Fixed Inner Profile		
Load	Outer Profile: Moment of 500 *Nm*		
Deformation	$2.442\ 10^{-5}$ m	$4.415\ 10^{-5}$ m	$2.764\ 10^{-5}$ m

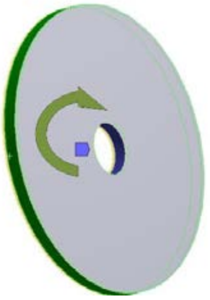

Figure 4 Loads and Supports. Support: Blue highlighted surfaces. Load: Green highlighted surface (see Table 3)

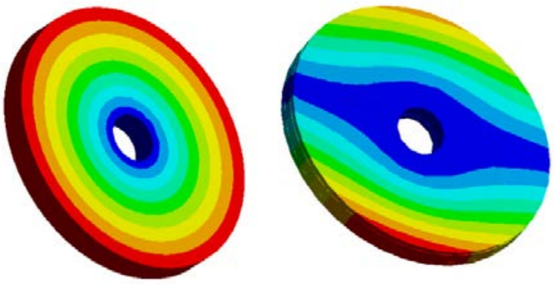

Figure 5 Left: Static analysis deformation pattern. Right: Modal analysis deformation pattern (First mode)

3.2. Joining / Texturing Design

The joining of the metal with the composite, will be conducted via thermoplastic adhesives, due to the many advantages offered by joining and has been previously stated. However, in order for such a joining to be feasible, texturing of the metal surface has to be done through laser etching technologies. The texturing has to be optimized in order for the best possible joining to be achieved. In this stage of the design, the interface between the adhesive and the metal part has to be modelled, with the use of a different “layer” with its own mechanical properties that will correspond to different texturing options. This will allow the modelling of many different configurations of the interfaces of the parts in hand, in order for the optimum selections to be made [12].

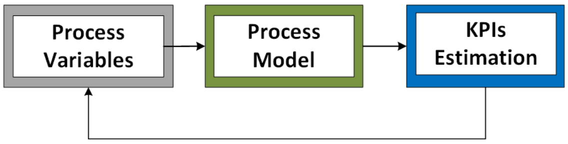

Figure 6 Process model framework

3.3. Lay-up Optimization

Up to this point, the optimization that has been discussed concerned the design of a hybrid part, whereas in this chapter, manufacturing (MFG) optimization issues will be discussed: the optimization of the parts’ manufacturing processes, in order for the best possible quality to be ensured.

The processes required for the manufacturing of hybrid parts, like those discussed in this study, are 1) the manufacturing of the steel part (conventional process e.g. press or unconventional e.g. laser cutting), 2) etching of the steel part, 3) lay-up of the adhesive and of the layers of the composite material, by using an automated tape placement system.

The input of each process is a set of process parameters and the KPIs are indicative of the manufactured part’s quality. As a result, each process can be optimized by using as input the process parameters that lead to the maximization of its KPIs. In order for those process parameters to be calculated, a simulator, capable of calculating the KPIs that result from each set of process parameters, has to be created for each process. More specifically, these simulators will have as input the process parameters and the KPIs as their output. In this way, the selection of the optimum process parameters will be possible. This procedure has to be followed for all the processes involved and it can be seen in Figure 6. This is certainly a general concept that has to be specifically adapted to each process. The adaptation of this strategy to the lay-up process can be seen in Figure 7.

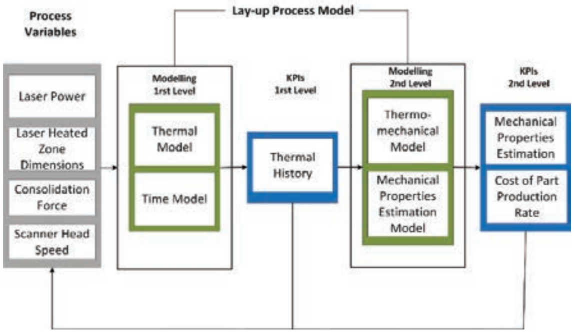

Figure 7 Lay-up process model framework

3.4. Other Modelling Details

There are other factors that should be taken into account such as the size effects [13] and the effect of moisture [14]. More specifically, the macro-behavior of the part and as a result its mechanical properties, depend on the part's microstructure. The smallest element to be used, which encompasses the macro-behavior properties of the part, has to be taken into account in order for the modelling results to be accurate (size-effects). Concerning moisture, it can have a degradation effect on the mechanical properties of the composite part, especially on the composite and the joining between the materials.

Table 5 Types of data of the data flow of Figure 8

Category	Type	Examples
A1	Configuration Requirement	Interface Strength
A2	Configuration Requirement	Number of Plies
A3	Configuration Requirement	Compaction Force
B1	Performance Indicator / Criterion	Polymerization Time
B2	Performance Indicator / Criterion	Manufacturability
B3	Performance Indicator / Criterion	Roughness

4. Information Exchange between the steps

4.1. Type of Information and Requirements

There are different types of actions that should be taken in each stage of the design and manufacturing, which have different requirements as well. In Figure 8, the action sequence of the design and manufacturing of the hybrid metal-composite parts can be seen. Furthermore, the types of data and examples in each category, can be found in Table 5. The purpose of this stage, in the design procedure, is the determination of the interdependencies between the requirements of each design and manufacturing stage. The requirements of the latter, as well as the former stages, have to be taken into account when the decision making process of each stage takes place. This will lead to a manufacturing plan that will be characterized by integrity: the purpose of each stage and its interdependencies will be clear, thus, minimizing the possibility of costly mistakes.

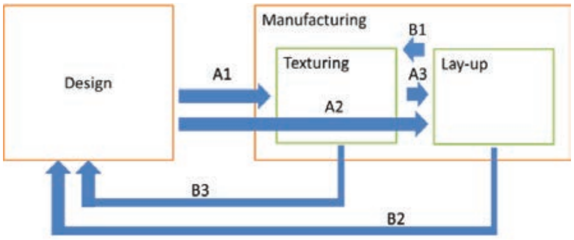

Figure 8 Data flow and courses of actions during hybrid parts design and manufacturing

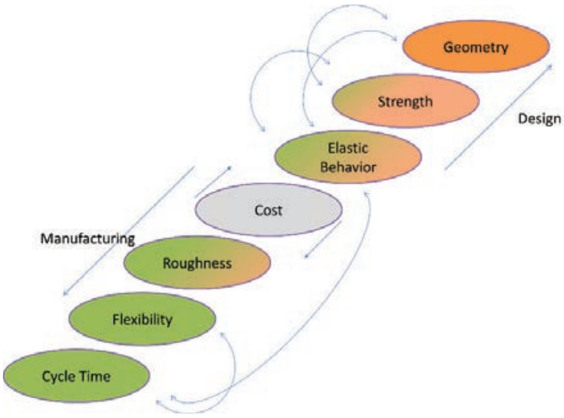

Figure 9 Hierarchy of criteria in design and manufacturing

4.2. Type of Information and Requirements

According to the industrial sector for which a part is designed, different weighing has to be made in the criteria used for design decisions. More specifically, in aerospace industry, the weight of parts is of paramount importance, and the production time is not as important; whereas, in the automotive industry the minimization of production time is very important. The example of the parts, presented in chapter

3, is indicative of this: The completely metal part and the second hybrid part can fulfil the same role, since they almost have the same mechanical properties (static and dynamic behaviour). However, the hybrid part is thicker and lighter than the metallic one, possibly having a higher production time. Consequently, each part has different advantages and disadvantages, and the decision as to which set-up is the best for each different case, has to be determined by prioritizing the different criteria (Figure 9).

5. Conclusions

In this paper, an optimization strategy for the design and manufacturing of hybrid metal-composite parts has been proposed. The advantage of utilizing this strategy is the reduction of the time needed for a successful design procedure, which is a complex one, because of the many design parameters that have to be defined. Also, the superiority of the static and dynamic mechanical properties of hybrid parts, while simultaneously maintaining lower weight than fully metal parts, has been validated through simulations.

As far as future work is concerned, the use of Computer Aided Process Planning (CAPP) would contribute to facilitating the decision making procedure. More specifically, CAPP helps in the establishment of connections between design and manufacturing [15] increasing the effectiveness of the decision making, both in design and in manufacturing.

Acknowledgements

This work is under the framework of EU Project Communion. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 680567.

References

[1] Lamontia, Mark A., et al. "Manufacturing flat and cylindrical laminates and built up structure using automated thermoplastic tape laying, fiber placement, and filament winding." Sampe Journal 39.2 (2003): 30-43.

[2] Brecher C., et al, “Cost effective High Speed Production of Multi-Material Componenets by Selective Tape-Placement”, 10th International Conference on Composite Science and Technology

[3] Ucsnik, S., et al. "Experimental investigation of a novel hybrid metal–composite joining technology." Composites Part A: Applied Science and Manufacturing 41.3 (2010): 369-374.

[4] Thoppul, Srinivasa D., Joana Finegan, and Ronald F. Gibson. "Mechanics of mechanically fastened joints in polymer–matrix composite structures–a review." Composites Science and Technology 69.3 (2009): 301-329.

[5] Kinloch, Anthony. Adhesion and adhesives: science and technology. Springer Science & Business Media, 2012.

[6] Pahl, Gerhard, and Wolfgang Beitz. Engineering design: a systematic approach. Springer Science & Business Media, 2013.

[7] Tandon, Gyaneshwar P., et al., eds. Experimental Mechanics of Composite, Hybrid, and Multifunctional Materials, Volume 6: Proceedings of the 2013 Annual Conference on Experimental and Applied Mechanics. Springer Science & Business Media, 2013.

[8] Available online at : http://www.hexcel.com/Resources/DataSheets/Brochure-Data-Sheets/Prepreg_Technology.pdf . Last accessed on 25/04/2016

[9] Gürdal, Zafer, Raphael T. Haftka, and Prabhat Hajela. Design and optimization of laminated composite materials. John Wiley & Sons, 1999.

[10] Available online at http://www.hexcel.com/Resources/DataSheets/Prepreg-Data-Sheets/M21_global.pdf . . Last accessed on 25/04/2016

[11] Available online at http://www.epotek.com/site/administrator/components/com_products/assets/files/Style_Uploads/301-2%20Rev%20XII.pdf. Last accessed on 25/04/2016

[12] Davies, P., B. R. K. Blackman, and A. J. Brunner. "Standard test methods for delamination resistance of composite materials: current status." Applied Composite Materials 5.6 (1998): 345-364.

[13] A. Papacharalampopoulos, P. Stavropoulos, C. Doukas, P. Foteinopoulos, G. Chryssolouris, "Acoustic emission signal through turning tools: A computational study", (CIRP CMMO) Procedia CIRP, 14th CIRP Conference on Modelling of Machining Operations, 13-14 June, Turin, Italy (2013)

[14] Rangaraj, Sudarshan V., and Lloyd V. Smith. "Effects of moisture on the durability of a wood/thermoplastic composite." Journal of Thermoplastic Composite Materials 13.2 (2000): 140-161.

[15] Chryssolouris, George. Manufacturing systems: theory and practice. Springer Science & Business Media, 2013.