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Environmental impact assessment of thermo-stamping carbon fibres reinforced polyphenylene sulfide composite parts

V. Lacoma^{a,b}, J.-L. Bailleul^c, S. Moisan^b, C. Binetruy^a, O. Kerbrat^d

a: Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44000 Nantes, France – vincent.lacoma@ec-nantes.fr

b: Nantes Université, IRT Jules Verne, F-44000 Nantes, France

c: Nantes Université, CNRS, Laboratoire de thermique et énergie de Nantes, LTeN, UMR 6607, F-44000 Nantes, France

d: Univ Rennes, ENS Rennes, CNRS, Gem, UMR 6183, F-35000 Rennes, France

Abstract: *The use of composite materials instead of metals for aircraft parts has long been identified as a way of improving their environmental performance, as the weight savings reduce fuel consumption. In the context of environmental transition, it is important to improve the environmental impact of each step of the lifecycle. However few studies have described the environmental performance of composite part manufacturing. In the present study, we therefore conducted a complete environmental analysis of the thermo-stamping of carbon-fibre-reinforced polyphenylene sulfide (CF/PPS) composite parts using a Life Cycle Assessment based framework. First, to define the system's boundaries, the manufacturing process was described as a unit process sequence associated with the consumption and waste of materials and energy (i.e. elementary flows). Data were then collected from experimental measurements, databases, and literature for each flow. These data were used to produce an environmental assessment, highlighting the environmental impact hotspots of CF/PPS part thermo-stamping.*

Keywords: Environmental impact; manufacturing process; thermoplastic composites; thermo-stamping

1. Introduction

Polymer composites reduce the weight of structural parts, owing to their good strength-to-weight ratio compared with traditional materials such as metals. In aircraft, weight reduction reduces fuel consumption, meaning that composite parts have a smaller environmental impact across their life cycle [1]. Therefore, polymer composites have long been identified as an efficient way of reducing the environmental impact of the aeronautical sector. In the current context of environmental transition, everyone involved in the life cycle of aeronautical parts needs to find ways of reducing their environmental impact, and this includes the impact of the manufacturing stage. To this end, we carried out an environmental impact assessment of the carbon fibres reinforced polyphenylene sulfide (CF/PPS) thermo-stamping process. This process was chosen because it is already used in the aeronautical industry.

To the best of our knowledge, few articles have so far focused on the environmental impact of the thermo-stamping manufacturing process, in terms of detailed inventory data and associated environmental assessments. In a recent comparison of manufacturing processes, Wegmann *et al.* undertook an environmental assessment of a polycarbonate/glass fibre car

bonnet manufactured by thermo-stamping [2]. The authors used inventory data yielded by thermodynamic calculations and picked from the ecoinvent database. However, their environmental assessment of the manufacturing step was energy-oriented and did not include other elementary flows. Several studies have involved the environmental analysis of processes close to thermo-stamping, including the preform matched die process [3], cold diaphragm forming process [4], and automated tape laying coupled with thermoforming [5], but again focusing mainly on energy consumption. The lack of environmental data for the thermo-stamping process makes it difficult to identify its environmental hotspots and thus to set the priorities for enhancing its environmental performance. In the present study, we therefore conducted an environmental assessment of CF/PPS part thermo-stamping.

After introducing the context, we describe the methodology used for the environmental assessment of the CF/PPS thermo-stamping process (Section 2). This is followed by a comprehensive inventory analysis and environmental assessment (Section 3), after which we discuss our results (Section 4), and present our conclusions (Section 5).

2. Methodology for the environmental analysis of the CF/PPS thermo-stamping process

This article is based on the Life Cycle Assessment (LCA) framework, the standardized methodology (ISO 14040 and ISO 14044) for environmental analysis.

2.1. Scope of the study

The material used in this study was semi-crystalline CF/PPS (Toray Cetex® TC1100), in the form of consolidated sheets of 14 ply and 4.34 mm thick. The stamp-forming process we studied allows finished parts to be manufactured from semi-finished reinforced composite sheets, as shown in Figure 1. Preform heating was performed using a Sopara infrared (IR) composite oven. A 75T SCAMEX press was used for the stamping step. The process also involved preform cutting using an OMAX ProtoMAX abrasive water jet (AWJ), robot arm handling, and post-process machining. For each unit process, we listed the consumption and waste of all the materials and energy (i.e. elementary flows). All the elementary flows considered in the environmental analysis are shown in Figure 1. As the thermo-stamping process heats thermoplastic materials to high temperatures to soften the polymer matrix, emissions to air may take place as a result of material degradation and material additive vaporization mechanisms [6]. Two types of emissions may occur: particulate matter (PM) and gaseous compound such as volatile organic compounds (VOCs). According to the literature, the gases emitted during PPS degradation are mainly hydrogen sulfide (H_2S) and benzenethiol [7].

In the present study, our functional unit was a 250 x 200 x 4.34 mm CF/PPS part, manufactured in France using the thermo-stamping process. The composite was heated to 370 °C in the IR oven and then stamped in a mould at 100 °C with a 200 kN closing force. These process parameters are representative of real-world CF/PPS part thermo-stamping [8]–[12]. We assumed that scraps would mainly be generated at the preprocessing step (90%), and only a few at the postprocessing step (10%). Based on industrial observations, we expected successive part production cycles to overlap. In other words, while one part was being stamped, the next preform would be heated in the IR oven. As a consequence, machine idling time would be shorter.

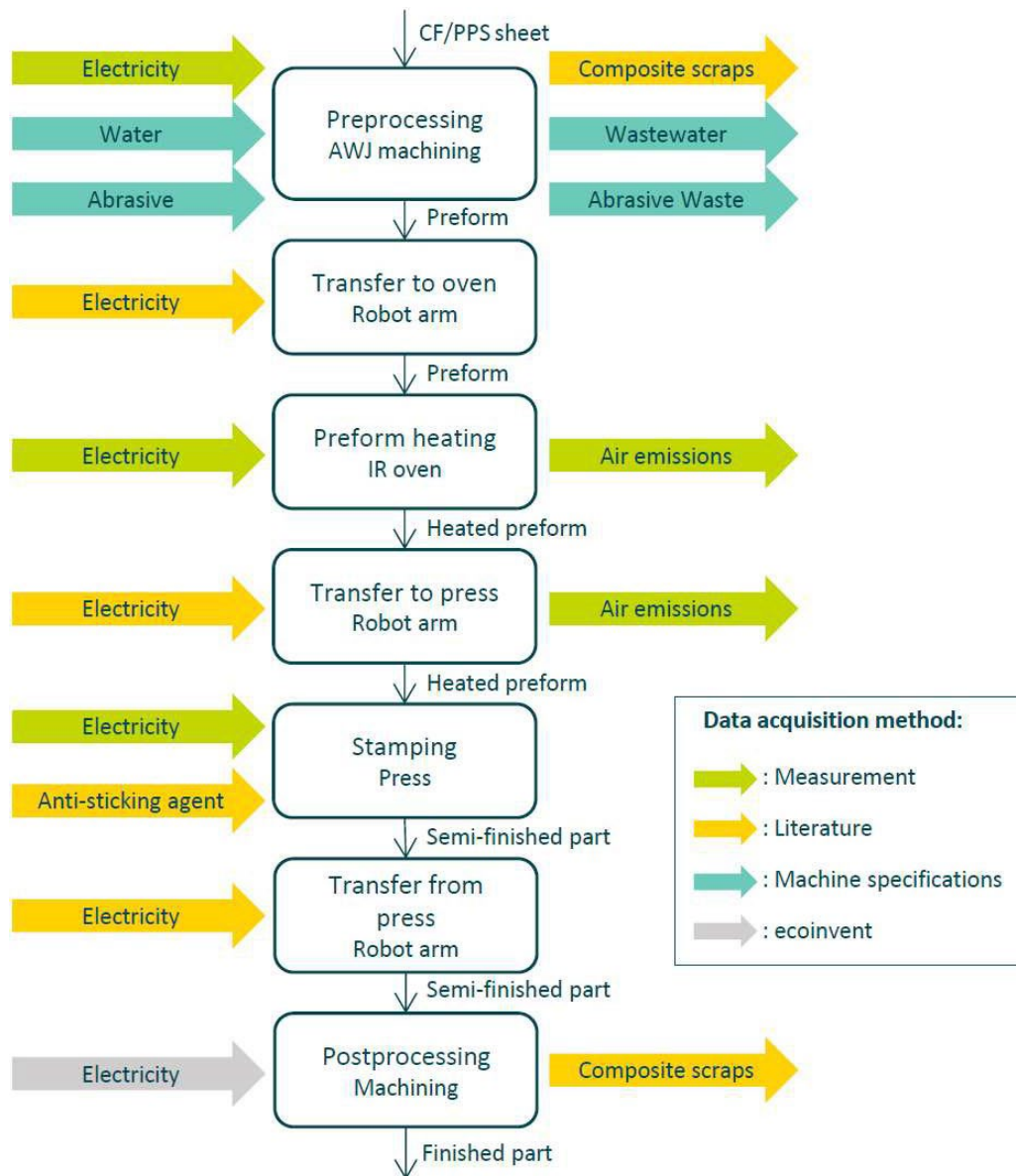


Figure 1: Thermo-stamping process description

2.2. Inventory data collection

Inventory data related to the process described in Figure 1 were collected through experimental measurements and from machine specifications, published studies, and ecoinvent databases. In Figure 1, the origins of the data for each elementary flow are colour-coded. Electrical energy consumption and air emissions were measured experimentally. The active power consumed by the machines was measured with a Fluke 434 II power quality and energy analyser with Fluke i30s current clamps. A Q-Trak (TSI) indoor air quality monitor with 987 VOC probe capable of detecting H₂S and benzenethiol was used to measure gaseous compound emissions. A DUSTTRAK (TSI) was also used to detect 0.1-10 µm PM emissions. Measurements with both instruments were performed at the output of the IR oven exhaust system during CF/PPS heating tests. As emissions from thermoplastics increase with the temperature [13], the temperature of the different tests was set to the maximum (370 °C) used for CF/PPS thermo-stamping [8]–[12], to maximize emissions during the tests.

2.3. Environmental assessment

The environmental impact was assessed using SimaPro software with the ecoinvent v3.5 database and the Impact 2002+ v2.15 method. Robot handling steps were summed as a single unit process. Material consumption was considered separately from the unit processes. Transport steps were excluded, and landfill was chosen as the waste treatment scenario. Polydimethylsiloxane was chosen as the anti-sticking agent, in line with Wegmann *et al.* [2]. To assess the environmental impact of the CF/PPS semi-finished material, we only considered PPS and CF production and not the semi-product manufacturing step. PPS production was modelled using ecoinvent v3.5. We computed the environmental impact of carbon fibre production using the data from Khalil *et al.* [14] and Duflou *et al.* [15] aggregated by Forcellese *et al.* in [16]. Our environmental analysis only included CF/PPS overconsumption. We adopted this approach in order to focus on improving the manufacturing process. Thus, the amount of CF/PPS used for the part was excluded from the elementary flows, as no actions on this flow are possible at the manufacturing stage: it can only be improved at the part design stage, which was beyond the scope of the present study.

3. Environmental results

3.1. Inventory analysis

The results of the inventory analysis of the CF/PPS thermo-stamping process are shown in Table 1. First, part material and scraps across the whole process were summed to obtain CF/PPS material consumption. Scrap data were extracted from the literature for different processes [17]–[25] and averaged to obtain the total scrap rate (34%). Using this rate, CF/PPS consumption was estimated at 5.1E-1 kg.

Air emission measurements were inconclusive, as no gaseous compound or PM emissions were detected. Anyway, emissions data have been computed assuming that the emissions are approximately equal to the detection threshold of the measuring devices and occur above the PPS melting temperature. Thus, the gaseous compound detector detection threshold and standard deviation of the PM measurements were assumed to be the emission values. To overestimate the environmental impact of the air emissions, we chose the worst scenario: hydrogen sulfide (H₂S) as the only emitted gaseous compound and 2.5 µm as the maximum diameter for PM emissions.

Table 1: Inventory dataset for the part thermo-stamping step
(E_i: Electrical energy consumption in Step i; m_i: mass of i flow; V_i: volume of i flow)

Unit process	Inventory data	Data collection methodology
AWJ preform cutting	$E_{AWJ\ cut} = 8.93E+05\ J$	Scaled on experimental measurements on the OMAX ProtoMAX AWJ machine
	$V_{water} = 3.2\ L$	Scaled on OMAX ProtoMAX AWJ machine specifications
	$m_{abrasive} = 4.37E-01\ kg$	
	$m_{AWJ\ scraps} = 1.56E-01\ kg$	Arbitrary value set at 90% of total scrap
	$V_{wastewater} = 3.2\ L$	Set equal to water and abrasive input
	$m_{abrasive\ waste} = 4.37E-01\ kg$	
IR oven heating	$E_{oven} = 3.07E+06\ J$	Scaled on experimental measurements on the SOPARA IR oven
	$m_{oven\ H_2S} = 4.27E+02\ mg$	Based on experimental measurements and measuring machine specifications
	$m_{oven\ PM\ 2.5} = 2.45\ mg$	

Robot arm handling	$E_{\text{robot}} = 8.17\text{E}+04 \text{ J}$	Computed with Chemnitz <i>et al.</i> model for Comau SMART SiX robot arm energy consumption during an 8 s motion [26]
	$m_{\text{robot H}_2\text{S}} = 7.60\text{E}+01 \text{ mg}$	Based on experimental measurements and measuring machine specifications
	$m_{\text{robot PM}_{2.5}} = 4.36\text{E}-01 \text{ mg}$	
Stamp forming	$E_{\text{press}} = 5.37\text{E}+06 \text{ J}$	Scaled on experimental measurements on 75T Scamex press
	$m_{\text{anti-stick}} = 1.22\text{E}-03 \text{ kg}$	Scaled using averaged literature data for anti-sticking agent consumption in different composite manufacturing processes [2], [16], [18], [27], [28]
Machining	$E_{\text{machining}} = 1.99\text{E}+05 \text{ J}$	Taken from ecoinvent v3.5 database model for chromium steel milling, because of its higher energy consumption factor than other metal milling models found in ecoinvent v3.5
	$m_{\text{machining scrap}} = 1.73\text{E}-02 \text{ kg}$	Arbitrary value set at 10% of total scrap

3.2. Environmental assessment

Environmental impact assessment results are set out in Figure 2. CF/PPS material overconsumption was identified as the primary contributor to environmental impact. Regarding the global warming impact category, 90% of the computed impact came from the material overconsumption flow. The heating and stamp-forming steps each had also a significant environmental impact. For the global warming impact indicator, 3% of the impact was caused by the IR heating and 6% by the stamp forming steps. It was the energy consumption flow that drove the environmental impact of these two unit processes. Focusing on air emissions, these two elementary flows accounted for three environmental impact indicators: PM_{2.5} emissions contributed to around 0.11% of the respiratory inorganics environmental impact; and H₂S emissions contributed to 0.19% of non-carcinogens and 5.7% of aquatic acidification environmental impacts.

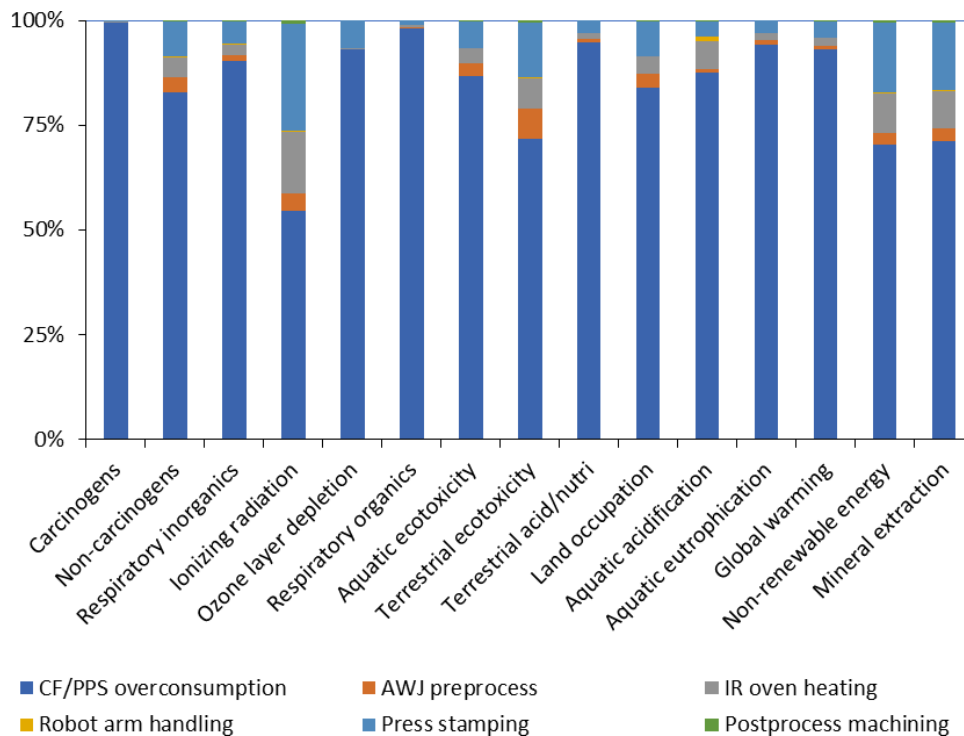


Figure 2: Environmental impact assessment of CF/PPS part manufacturing

4. Discussion

In the present study, we conducted an environmental assessment of CF/PPS part thermo-stamping. Results showed that CF/PPS material overconsumption was by far the greatest contributor to environmental impact, despite the underestimation of the environmental impact of CF/PPS production (PPS and CF production was considered, but not semi-product manufacturing). The energy consumption for the heating and stamping unit processes was also the source of significant impacts. In order to develop efficient environmental impact improvement strategies, the focus needs to be on the environmental hotspots we identified. However, our results need to be interpreted with care, as CF/PPS overconsumption was based on literature data. Furthermore, process specificities and part geometry were not considered, even though these two aspects strongly influence material consumption. For example, the blank holders used in the process caused material overconsumption. Expected part geometry also affected the preform's in-plane shear deformation on the mould, which was correlated with material consumption.

As experimental measurements were inconclusive, we estimated air emissions by coupling these inconclusive results with the specifications of the measuring machines. This led to overestimated emissions. Despite this, computing the associated environmental impact showed that air emissions had a negligible influence on the environmental impact of the process. This was still an advance, as very few studies have considered air emissions in thermoplastic composite manufacturing environmental assessments.

Our conclusions should be treated with caution, as the environmental results we computed pertain to a single case study of part manufacturing with a fixed set of parameters. Thus, the results cannot easily be generalized to the thermo-stamping process.

5. Conclusion

The use of composite materials has long been identified as a solution for decreasing the environmental impact of aircraft parts, thanks to the fuel savings afforded by the lighter structures. In the context of environmental transition, the environmental impact of composite parts has to be improved across their lifecycle. The present study focused on the environmental impact of the CF/PPS thermo-stamping process. Based on a complete description of this process, we assessed inventory data for each elementary flow we identified, using various strategies (experimental measurements, database and literature data). Using these data, we assessed the environmental impact of each part manufacturing step. This assessment highlighted two environmental hotspots: CF/PPS material overconsumption and energy consumption during the heating and stamping unit processes. Therefore, the present study helped to make up for the lack of environmental data for the thermo-stamping process. Nevertheless, it only focused on one part with one set of process parameters, which is not enough to draw general conclusions about the process.

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