OPTIMIZATION OF ‘COLD’ DIAPHRAGM FORMING PROCESS BY MEANS OF AN EXTENSIVE COST ANALYSIS STUDY

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SUMMARY

With the aim of manufacturing composite material products of a specified quality at minimum cost, a generic concept has been developed in order to optimize the ‘cold’ diaphragm forming (DF) process with respect to cost effectiveness. To this end, cost analysis of components produced using the DF technique is performed. The analysis is based on the principles of Activity Based Costing methodology, and is fully parametric, as far as, the process parameters of DF are concerned. Using available industrial and simulation cost and process data, Cost Estimation Relationships (CERs) are developed for all sub-processes of the DF process. The cost analysis has shown that the most cost-and time-consuming sub-processes (apart from the ‘material supply’ and the NDI sub-process which includes dimension measurements, C-Scan inspection etc) are ‘*preparation of the tool’* and ‘*preparation of the material’* respectively. Finally, the developed cost estimation software tool (LCAT) is applied for the optimal definition of the process parameters with respect to quality and cost.

1. INTRODUCTION

The production of lightweight structural and semi-structural composite components at low cost is of major importance in engineering applications. The selection of the optimal manufacturing process is one of the driving parameters that strongly affects the final cost of the component and therefore its viability. Reduction of manufacturing cost by simultaneously satisfying the quality requirements is critical for the application of composite materials in the aerospace, marine, civil and consumers’ industrial sectors. Diaphragm Forming is a promising method that could meet the above criteria of cost and quality. Due to the cost effectiveness potential, especially of the ‘cold’ Diaphragm Forming process [1], DF has become attractive as an alternative forming technique replacing conventional methods, such as autoclave, compression molding and pultrusion. Keeping in mind that any changes in process parameters or/and in part characteristics have strong influence on the cost of the final product, an extended cost analysis is needed in order to know in advance the product cost and decide whether to apply this method or which ‘version’ of the process is the most cost efficient.

In the present work, based on the aim of manufacturing composite material products of a specified quality at minimum cost, a generic concept has been developed in order to optimize the 'cold' diaphragm forming (DF) process with respect to cost effectiveness. In chapter 2 the DF process principles as well as a small review on the existing cost analysis methods are discussed. In-depth cost analysis has been performed for the DF manufacturing of a specific aeronautic component. The analysis is based on the principles of Activity Based Costing method. Using available industrial cost data and process data generated from numerical simulation by means of finite element analysis [2], Cost Estimation Relationships (CERs) were developed for all sub-processes of the DF process. The cost analysis has shown that the most cost-and time-consuming sub-processes (apart from the 'material supply' and the NDI sub-process which includes dimension measurements, C-Scan inspection etc) are '*preparation of the tool'* and '*preparation of the material'* respectively. Finally, the developed cost estimation software tool (LCAT) is applied for the optimal definition of the process parameters with respect to quality and cost.

2. BACKGROUND OF 'COLD' DIAPHRAGM FORMING AND COST ANALYSIS

2.1 Overview of 'Cold' Diaphragm Forming process

The cold diaphragm forming process is a forming process based on the Superplastic Forming (SPF) principles. For implementing the DF technique, thermoplastic prepregs or organic plates are fixed under vacuum between two thin, plastically deformable (usually polymeric) films, the so called diaphragms, which are clamped around the edges, as shown in Figure 1. Forming of the laminate over a heated tool occurs above the melt temperature of the thermoplastic matrix by applying a pressure gradient normal to the diaphragms. The formed part can be removed from the tool after having been cooled under pressure to a temperature, below which, structural stability of the laminate is achieved (often this temperature value is considered the *Tg*).

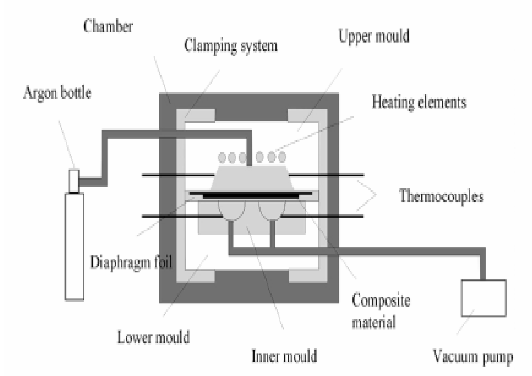


Figure 1:
'Cold' Diaphragm Forming Process scheme

2.2 Cost Analysis methodology principles

The driving force for the designers and manufacturers of aerospace components is always the reduction in cost and improvement in quality of parts [3]. Therefore, cost estimating can not be entirely left to accountants or salespeople if the process parameters sensitivity to quality and cost has to be taken into account in the overall cost estimation methodology. The manufacturing engineer should play a key role in optimizing the cost of a new or an existing product. Since cost is not known in advance of production, a cost estimation system is required. The cost estimating job becomes vital in the area of composite materials because the composite products must compete with their well developed metal competitors [4].

There are many approaches and methods that have been used to estimate the cost of a part from a manufacturing point of view [5-6]. Conventional costing methods either compare the recorded costs of a completed project with the new one (*analogous*) or divide the total cost incurred in a cost center by the units produced in the center to derive the cost per unit (*resource based* and *Industrial engineering*). Alternatively, there is a number of advanced methods (*First Order, ACCEM, Bottom up, ABC*) that are commonly known as *Technical Cost Modeling (TCM)* [6]. In general, some of them can be applied only in a later stage of the product, while others use only a few number of linear relations in order to connect the cost with the process parameters. Finally, several newly developed 'advanced estimation techniques' exist (*Feature Based, Fuzzy logic,etc.*) [6] but they are suitable only for specific applications. None of the above methods and models has been used in the literature in order to perform a cost analysis of Diaphragm Forming process.
Unlike comparative techniques, the Activity Based Costing (ABC) is a method that derives product costs as a sum of the costs of the activities that occur to make a product, either when it comes from a single process or from an entire production line. In general the ABC consists of the following four basic steps:
a)Identification of the activities or transactions that cause costs during the product development (sub-processes and main processes), b)Identification of the cost drivers to each sub-process, c)Assignment of costs to each sub-process via the creation of the Cost Estimation Relationships (CERs) and d)Summation of the costs of sub-processes that occur to 'make' a product.

3. PARAMETRIC COST ANALYSIS OF THE DF PROCESS

Following the above described ABC concept, both manufacturing process flow and process parameters are considered to be variable and after been defined, they can be used in order to calculate which is the minimum cost for certain quality objectives, like mechanical properties, dimensional tolerances, etc. which have been set by the product specifications.

3.1 Sub-processes of the DF process

'Cold' DF process can be divided into the following main sub-processes, which are schematically illustrated in Figure 2:
a) Material supply, which refers to the purchase of the raw material (prepreg), the diaphragms and the release agent.
b) Preparation of the tool, which includes cleaning of the tool and applying the release agent.
c) Preparation of the material and tool closing, which includes cutting of the prepreg and the diaphragms, placing them in the tool, clamping the tool, sealant application and vacuum pressure check.
d) Heating of the material up to the forming temperature with the assistance of infrared heaters. Additionally, forming, consolidation and cooling in ambient air are included to this sub-process.
e) Opening, demolding, rework, inspection dimension measurement and storage.

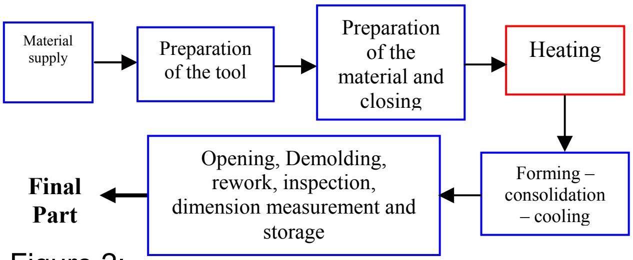


Figure 2:
Division of the DF process in sub-processes

Part Data	PAA [m^2]	Part area (mold side)
	WP [kg]	Weight of part
	NPL [/]	Number of plies
	PAP [m]	Perimeter of part
	$THPL$[m]	Thickness of each ply
	APL[m^2]	Area of each ply
	cmp	Complexity
	PPA[m^2]	Part projected area (in contact with the mold)
	ρ[kgr/m^3]	Prepreg mass density
Process Data	Ncl [/]	Number of clamps
	NH [/]	Number of heating elements
	D [m]	Distance between the material and the lamps
	Nd [/]	Number of diaphragms
	P_L [W]	Power of each lamp
	Npc[/]	Number of pieces produced per year
	Lf[years]	Estimated life of equipment
	Nm[/]	Number of maintenances
Cost Data	k_{pr} (cu/kgr)	Cost of the prepreg per kgr
	k_d (cu/m^2)	Cost of the diaphragm per m^2
	k_a (cu/kgr)	Cost of the releasing agent per kgr
	k_w (cu/hour)	Cost of the specialized worker per hour
	k_{inf} (cu/hour)	Cost of one infrared lamp switched on per hour
	K_{vac} (cu)	Vacuum pump cost
	Equipment cost	
	Maintenance cost	

Table 1:
Part, Process and Cost Data cost drivers

The basic 'Cost drivers' that were determined for cold DF process are presented in Table 1, where a distinction has been made to 'part' related data, 'process' related data and 'cost' data.
After the process 'cost drivers' have been identified, mathematical functions that express their relation to the consumption of the resources, the Cost Estimation Relationships (CERs), should be established. These functions as well as some secondary equations that are used for their definition are extracted from statistical, experimental or empirical data. The resulting CERs that were determined for 'cold' DF are the following:

a) Sub-process **1**: *Material supply*
In the majority of processes, one of the most important percentages of the total cost is material supply cost which, frequently exceed 50% of the total cost and therefore should be estimated with reasonable care. The total cost of material supply K_1 (cost unit-CU) is the sum of the cost of the prepregs K_{pr} , the cost of the diaphragm K_d and the cost of the releasing agent K_a including the handling costs:
$K_1 = K_{pr} + K_d + K_a$ where K_{pr}, K_d, K_a are defined based on experimental and historical data: $K_{pr} = k_{pr} \cdot 1.8 \cdot THPL \cdot APL \cdot NPL \cdot \rho$, $K_d = 1.6 \cdot k_d \cdot PPA \cdot N_D$, $K_a = 1.1 \cdot k_a \cdot PAA \cdot m_{ag} \cdot 2 = 0.22 \cdot k_a \cdot PAA$

b) Sub-process **2**: *Preparation of the tool (cleaning+applying releasing agent)*
The total cost of the preparation of the tool K_2 (CU) is the sum of the cost of the tool cleaning K_{cl} and the cost for the applying of the releasing agent K_{ap}:
$K_2 = K_{cl} + K_{ap}$ where:
$$K_{cl} = k_w \cdot t_{cl} = k_w \cdot (1 \cdot 2 \cdot PAA) = k_w \cdot (2 \cdot PAA),\ K_{ap} = k_w \cdot t_{ap} = k_w \cdot (0.1 \cdot PAA)$$

c) Sub-process **3**: *Preparation of the material and closing*
The cost of the preparation of the material and closing K_3 (CU) is the sum of the prepreg and diaphragm cut cost in the desired shape K_{cu}, the cost of the tool closing K_{tc}, the cost of the sealant application K_{se} and the cost of vacuum check K_{chva} :
$K_3 = K_{cu} + K_{tc} + K_{se} + K_{chva}$ where:
$$K_{cu} = k_w \cdot t_{cu} = k_w \cdot 0{,}25 \cdot PAP,\ K_{tc} = k_w \cdot t_{tc} = k_w \cdot (0.2 \cdot N_{cl} + 0.1 + 0.02),$$
$$K_{se} = k_w \cdot t_{se} = k_w \cdot (0.5 \cdot PAP + 1),\ K_{chva} = (k_w + k_{vac}) \cdot t_{chva} = (k_w + k_{vac}) \cdot 0.5 \cdot PAP \cdot cmp = k_w + k_{vac}$$

d) Sub-process **4**: *Heating*
The total cost of the heating K_4 (CU) is the cost of using the infrared heating elements K_{inf}: $K_4 = K_{inf} = k_{inf} \cdot t_4$

Since the combination of a TCM with a manufacturing simulation provides the ideal modeling environment, the necessary heating time is provided from the simulation results defined in a previous work [3]. After data regression analysis, the following exponential CER is suggested: $K_4 = \kappa_{\inf} \cdot e^{(-2.14 \cdot 10^{-3} \cdot NH + 1.58 \cdot 10^{-3} \cdot D + 0.24 \cdot TH + 4.23 \cdot 10^{-4} \cdot P_L + 4.74)}$

e) <u>Sub-process ***5:*** *Opening, demolding, rework, inspection dimension measurement and storage*</u>

The total cost of sub-process K_5 (CU) is the sum of the tool opening cost K_{op}, the demolding cost K_{de}, the rework cost K_{rw}, the NDT inspection cost K_{isp}, the dimension measurement cost K_{dim} and the storage cost K_{st}:

$K_5 = K_{op} + K_{de} + K_{rw} + K_{isp} + K_{\dim} + K_{st}$ where:

$K_{op} = k_w \cdot t_{op} = k_w \cdot (0.2 \cdot N_{cl} + 0.1)$, $K_{de} = k_w \cdot t_{de} = k_w \cdot 0.25 \cdot PAA$, $K_{rw} = k_w \cdot t_{rw} = k_w \cdot 0{,}25 \cdot PAP$,

$K_{isp} = k_w \cdot t_{isp} t = k_w \cdot (1 \cdot PAA \cdot cmp + 0.5)$, $K_{\dim} = k_w \cdot t_{\dim} = k_w \cdot 0{,}5 \cdot cmp \cdot PAA$,

$K_{st} = k_w \cdot t_{st} = k_w \cdot (0{,}05 \cdot WP + 0{,}16 \cdot PAP)$

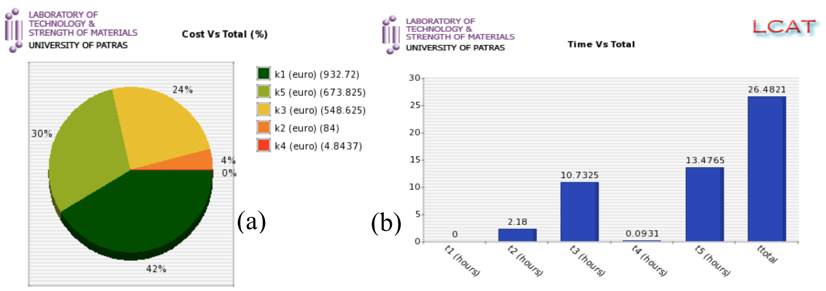
Although the main target of the present work is to estimate the cost in terms of recurring costs, the non-recurring costs, namely the capital cost K_{cap} of the machines used, is taken into account at the final step of the estimation in relation to the production rate (volume) using the following equation:

$K_{cap} = \dfrac{total\ equipment\ \cos t + ma\,\mathrm{int}\,enance\ \cos t \cdot N_m}{Npc \cdot L_f \cdot}$ where: $N_m = 2 \cdot Npc \cdot L_f$

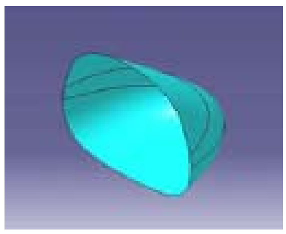
The total cost $\boldsymbol{K_{total}}$ of the formed product is the sum of the cost of each sub-process according to the following relation: $K = K_1 + K_2 + K_3 + K_4 + K_5$. The total process time $\boldsymbol{T_{total}}$ is the sum of the duration of each sub-process according to the following relation: $t_{total} = t_1 + t_2 + t_3 + t_4 + t_5$. It has to be mentioned that no learning curve effects are taken into account since the examined process is under development and therefore in a very early stage, which results to absence of a learning curve.

4. COST ESTIMATION RESULTS

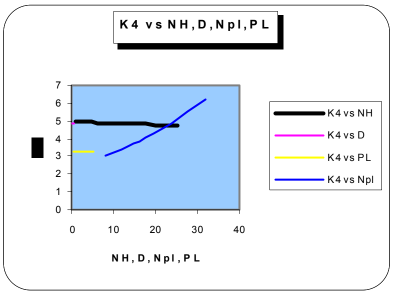
In order to identify basic trends and dependencies a cost sensitivity study of a typical aeronautic component manufactured by DF, Figure 3, was performed. Each parameter's contribution to the total part cost and total process time was calculated. Additionally, the major cost-and time-consuming sub-steps of the process were investigated in order to identify and improve the critical sub-processes and their critical process parameters. The most labor intensive step, apart from the 'material supply' and the NDI sub-process, are the '*preparation of the tool'* and on the other hand, the most time consuming sub-process is the '*preparation of the material'*, Figure 4.



<u>Figure 4:</u>
Percentage and values of the various sub-processes with regard to Cost (a) and Time (b)



<u>Figure 3:</u>
Typical Aeronautic component



In Figure 5, the contribution of the major cost drivers to the cost of sub-process '*heating*' (K_4) is presented. It may be observed that both linear and non linear dependencies between cost-drivers and K_4 are taken into account.

Figure 5:
Contribution of the major cost drivers to the cost of sub-process '*heating*' (K_4)

5. OPTIMIZATION OF PROCESS PARAMETERS

An optimization of DF process was performed with regard to quality and cost. The Ltsm Cost Analysis Tool (LCAT), was used in order to find the optimal process parameter combination for the entire process via evaluation trials, with regard to the minimum cost which satisfies the specified product quality requirements. LCAT was implemented in scripting language php (Hypertext Preprocessor). As a language that has been designed expressly for the Web, it brings many features and can handle various types of data with very high performance. In addition php can store results and data easily in a data base (ex. Mysql) for further data analysis. In our case php has been used as a development tool user friendly and easily accessible.
Input data is given coupled with a range (e.g. number of heating elements: 10-100 with 5 step) such as every possible combination and its respective cost is taken as an output. Also, as an output is taken the best process parameters combination in terms of cost and graphs showing the contribution of each sub-process to the total cost and time.
After the optimization performed, the optimal parameters combination in terms of quality and cost for the given data is shown in Table 3.

Process Data	*Ncl* [/]	10
	NH [/]	100
	D [m]	0.05
	Nd [/]	1
	P_L [W]	800
	Npc[/]	200
	Lf[years]	15
	Nm[/]	600

Table 3:
Optimal process parameter combination

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