Application of DFMA concept to evaluate the tooling cost for carbon fibre reinforced thermoplastic composites compression moulding processes

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Abstract

In the process of developing new manufacturing technology to make aircraft parts, a cost model has been proposed to evaluate the manufacturing costs of two compression moulding processes for carbon fibre thermoplastic composites. The first one aims to make a flat part from random discontinuous prepeg strands whereas the second produces a concave part from unidirectional continuous fibre prepeg sheet. In this study, DFMA concept was used to estimate the tooling costs for these two processes. Results obtained from the DFMA software of Boothroyd and Dewhurst Inc. was compared with the manual estimating costs conducted in the research manufacturing laboratory and the commercial prices. For the flat mould the costs estimated by the software are close to the internal manufacturing costs. In the case of the concave mould, they are significantly different.

1. Introduction

Recently carbon fibre reinforced thermoplastic composite has been becoming a candidate material to replace conventional materials for making parts in aerospace industry, due to possibilities of weight saving and forming of complex shape. However, in order to help making the decision for the changeover, it is important to be able to predict the costs of the new product in comparison with the existent one.

It has been demonstrated that approximately 70% of a product cost is fixed at the design stage (Boothroyd et al, 1994) [1]. Therefore, it is interesting to predict the manufacturing cost of a new product in the development stage. According to Haffner [2], the manufacturing costs are explicitly given by the following formula:

$$C_{Total} = C_{Material} + C_{Labor} + C_{Energy} + C_{Machinery} + C_{Tooling} + C_{Facilities} + \text{Overheads} \quad \textbf{(1)}$$

Despite the presence of some works related to the estimation and comparison of manufacturing costs of certain automotive thermosetting and thermoplastic injection moulded parts, the cost analysis data of thermoplastic composite parts manufactured by compression moulding are almost nonexistent. In the case of compression moulding the cycle time and the tooling costs are closely related to the geometry of the parts to be made of. The tooling costs can be estimated by DFM for machining costs and DFA for assembly costs modules of the DFMA commercial software of Boothroyd and Dewhurst Inc. The DFA approach was developed by Geoffrey Boothroyd, supported by National Science Foundation (NSF) grant at the University of Massachusetts in the mid-1970s. This method can help designers to design parts that would be handled and assembled automatically [3]. In early 1980s, Geoffrey Boothroyd and als developed a DFMA software version which was used by various industrial sectors particularly U.S industry and presented important manufacturing cost and time savings [4].

2. Scope and objective

This work is part of a research project on compression moulding processes to manufacture carbon fibres (unidirectional short and long fibres) reinforced thermoplastic composites parts. In order to develop the manufacturing cost modeling of the parts made with flat and concave moulds, this study aims to investigate the ability to estimate the mould costs using DFMA software.

3. Composite Parts Manufacturing Processing

Two compression moulded carbon/PEEK composite parts were studied in this project. The first one is a flat plate made of short fibre randomly oriented strands and the second one is a concave part made of unidirectional laminate.

3.1 Compression moulding of flat plate

The studied part made is a flat plate of 280mm x185mm x 6mm dimension made of long discontinuous fibre strands of 25.4 mm x 12.7 mm x 6 mm dimension, which are slit manually or automatically from unidirectional prepreg tape whose width is 304.8 mm. These strands are distributed in such a way to assure their random orientation in the mould. A six step manufacturing cell of the flat plate is shown in figure 1:

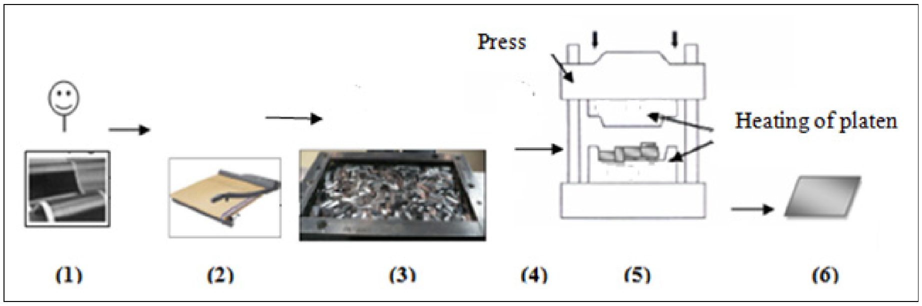

Figure 1 Manufacturing cell of flat plate: (1) placing material in the cutter, (2) cutting of material into strands (manual cutter), (3) distribution randomly of strands in the mould, (4) closure and transfer of the mould to the press, (5) heating of platens and compression moulding of flat plate, (6) demoulding.

Figure 2 shows two halves of the flat mould manufactured in Industrial Material Institute-National Research Council of Canada (IMI) [5] and the manufactured flat plate.

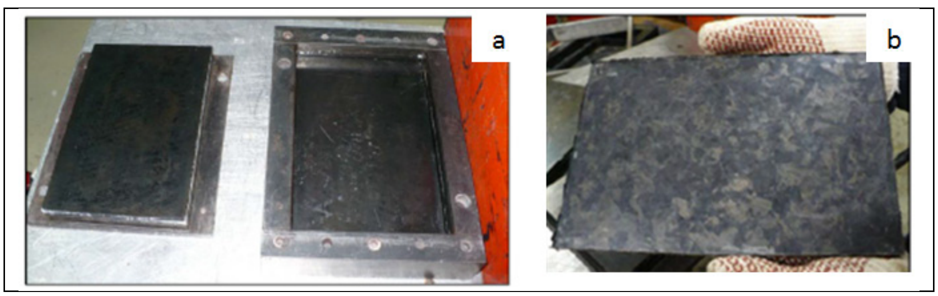

Figure 2 (a) Two halves of flat mould, (b) Manufactured flat plate

In order to make the cost analysis of the moulds using the DFM software for both flat and concave moulds, the material selected is the high carbon steel. The proprieties of the mould material are presented in table 1.

Table Proprieties of the mould material [6](Adapted)

Propriety at 20 C	Units	Value
Density	Lb/in^3	0,283
Thermal conductivity	W/m.K	34
Specific heat	J/Kg.K	460
Modulus of elasticity	MPa	890 – 1030 [a]

[a] According to EN 18265, scale B2

3.1.1. Flat mould manufacture processing

The flat mould is manufactured at the IMI machine shop. It composed of two components: the punch, the cavity. The mould manufacturing process is divided into two steps: The first step is to cut two parts of 19 inches long, 15 inches wide and 6 inches high from a rectangular bar stock. The second step consists to cut and remove material from the parts. For making the punch and the cavity, it is necessary to use milling and drilling operations. The milling operation is divided into two categories: face milling and pocket milling. The face milling is used to make the punch and the pocket milling is used to make the cavity. The drilling operation consists to drill holes in the side of the wall of the cavity block permitting to set up six control thermocouples and four bolting holes in the sides of punch block permitting to attach the last one to the heating platen of the press. After the machining operations, all the surfaces of the moulds are polished and inspected afterward.

<u>Flat mould features data:</u> As mentioned before, the punch is made by milling and drilling operations. The milling machine is used to make features such as faces around the punch and to make pocket for cavity mould. The drilling machine is used to make features such as holes in the wall of the cavity. The table 2 presents the features manufacturing data for the punch and the cavity.

Table 2 Features manufacturing data

Mould	Features	Machining operation	Dimension							Repeat count	Remarks
			W	L_1	D_1	D_2	L_2	A	D4		
			in	in	in	in	in	in^2	in		
Punch	Faces	Rough and finish face milling	4	52	2,75	-	-	-		1	$L_1 = 19 \times 2 + 7 \times 2 = 52$ in Breakdown of L_1
	Holes	Drilling multiple holes	-	-	-	0,5	4	-	-	4	-
Cavity	Pocket	Rough and finishing single pocket end milling	-	-	-	-	-	77	3	1	$A = 11 \times 7 = 77$ in^2
	Holes	Drilling multiple holes	-	-	-	0,5	4	-	-	10	-
Cavity and punch	All machined features	Polishing and buffing	All machined surfaces								
	All machined features	Inspection visually	All surfaces the mould								

DFM costing results: The mould cost results obtained by DFM costing program for punch and cavity are presented in Table 3 and table 4 respectively.

Table 3 Punch block costs

Process chart	Total cost par part ($)	Cost rate (%)
machining /cut from stock process	**1769,5**	100
Stock process	272,62	15,4
Worpiece	268,71	15,18
Abrasive cut off	3,92	0,22
Generic CNC machining center	**1429,73**	80,79
Set up/load/unload	40,23	2,27
Rough and finish face mill	1367,12	77,26
Drill mutiple holes	14,18	0,8
Polish and buff	**57,78**	3,26
Inspect visually	**9,37**	0,53

Table 4 Cavity block costs

Process chart	Total cost par part ($)	Cost rate (%)
machining /cut from stock process	**1009,23**	100
Stock process	272,62	**27,01**
Worpiece	268,71	26,62
Abrasive cut off	3,92	0,38
Generic CNC machining center	**677,16**	**67,09**
Set up/load/unload	52,08	5,16
Rough and finish pocket end mill	584,79	57,94
Drill mutiple holes	35,91	3,55
Polish and buff	**53,94**	**5,34**
Inspect visually	**5,51**	**0,54**

Note: the labor rate used in the software is Cad $75/hour

Flat mould costs vs. production volume: Flat mould costs vs. production volume for punch and cavity blocks are illustrated in figures 3 and 4 respectively.

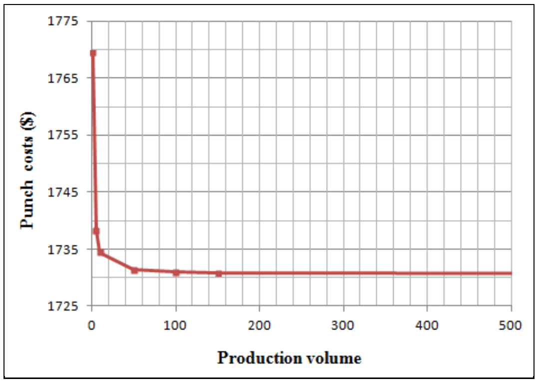

Figure 3 Punch block costs vs. production volume

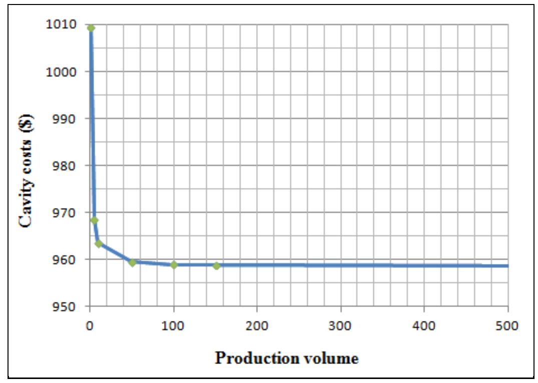

Figure 4 Cavity block costs vs. production volume

<u>Flat mould costs breakdown</u>: Flat mould costs breakdown for punch and cavity are illustrated in figures 5 and 6 respectively.

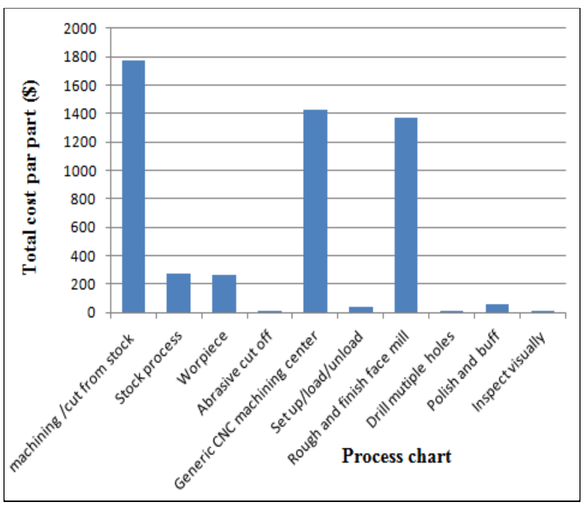

Figure 5 Breakdown of punch costs

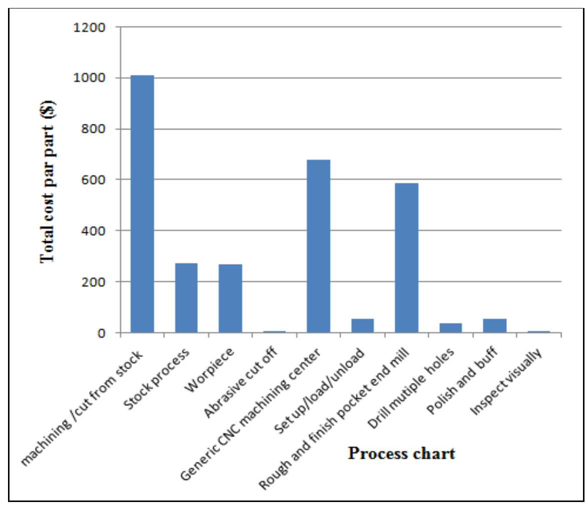

Figure 6 Breakdown of cavity costs

<u>DFM and workshop tooling cost estimation comparison</u> (Table 5):

Table 5 DFM and workshop tooling cost estimation comparison

Item	DFM	Workshop
Material costs ($)	542,82	540,00*
Manufacturing costs($)	2235,91	2325,00
Nickel coating ($)	-	600,00

**The mould material used in workshop is steel P-20.*

3.2. Compression moulding of concave part

The concave part is made from a laminate of continuous fibre prepeg plies of carbon/PEEK using a mould which has been designed at the University du Québec à Trois-Rivières (UQTR) and manufactured by a contractor. The part having the dimension of 228.6 mm x 152.4 mm x 4 mm is compressed by means of a hydraulic press after preheated in an infrared radiation oven. The manufacturing cell of the concave part is divided into six activities as shown in figure 7.

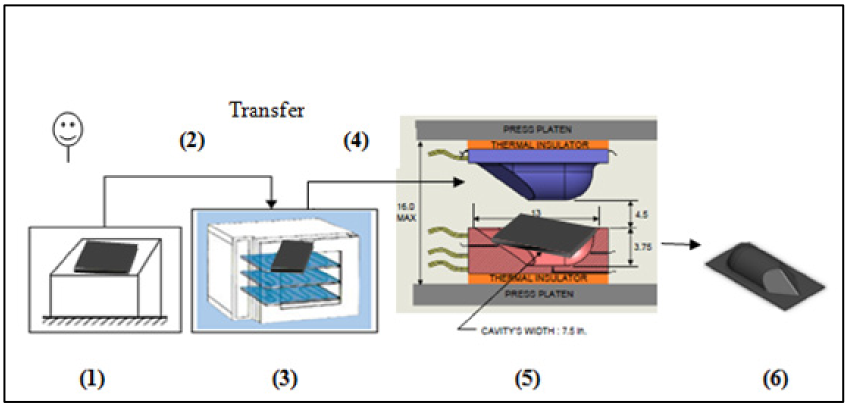

Figure 7 Manufacturing cell of concave part: (1)preparation of flat plate, (2) placing the plate in the IR oven, (3) heating the plate in the IR oven, (4) transfer of heated plate to press, (5) compression moulding of part, (6) demoulding of the cooled part.

Figure 8 presents two halves of the mould which are machined into final shapes by PCM Innovation company, subcontractor of UQTR[7] and the top and bottom views of the concave part which consists of quarter sphere, half cylinder and two slanted surfaces [8].

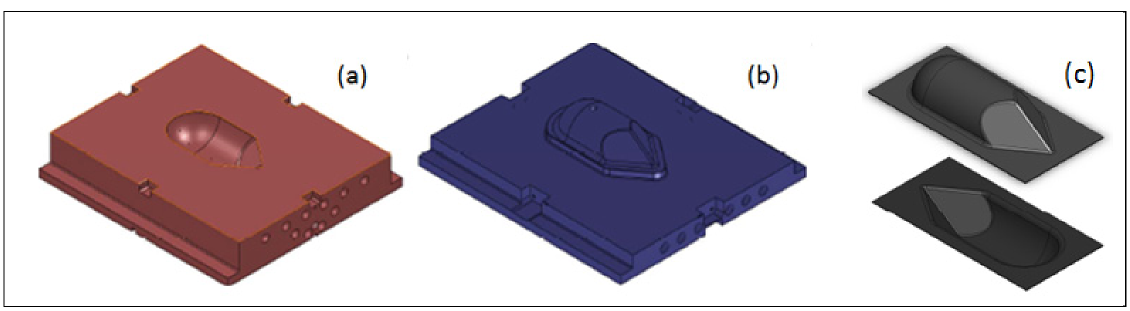

Figure 8 (a) Cavity block, (b) Punch block and (c)The top and bottom views of concave part

3.2.1. Concave mould manufacture processing

The first step is to cut two parts from rectangular bar stock. Each part shown in figure 13 is 12,5 inches long, 11,5 inches wide, and 2,188 inches high for the cavity or 2,768 inches high for the punch. The geometry of the parts is imported from Solidworks® software data to DFM program. The cavity is made with quarter sphere, half cylinder and two slanted surfaces. The second step is to cut and remove material from the parts. For making the punch and the cavity, it is needed to use milling and drilling operations. For the cavity, the part is submitted to milling operations to make features such as faces, slots, and pocket, and then to drilling operation to make different holes. For the punch block, the part is submitted to milling operations to make features such as faces, slots, and punch and then submitted to drilling operation to make different holes. After machining and polishing, the cavity block thermal insulator are fixed to mould base by four clamping devices, then the mould was assembled and checked to make sure the two halves mould fit together properly as shown in figure 9 [7]. The alignment is assured by four guide pins which are side lock devices located in the punch block.

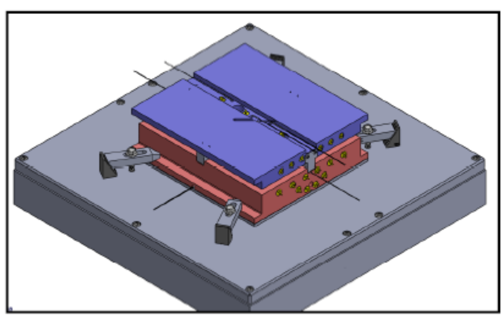

Figure 9 Mould assembly

<u>Features manufacturing data:</u> The tables 6 and 7 present the manufactured features data for punch and cavity blocks with machined volumes of 151,081 in³ and 248,85 in³ respectively.

Table 6 Features manufacturing data for punch block

Features	Machining operation	Dimension (in)								Repeat count	Remarks
		W	L_1	D_1	D_2	L_2	D_3	D	L_3		
Faces	Rough and finish face milling	4,1	25	1,568						2	
		3,1	3,3	1,568						1	
		2,9	3,3	1,568						1	
		0,75	25	0,7						2	Calculated curvature surfaces are supposed to be neglected
		0,722	1,09	1,568						1	To mill remaining spherical faces
		0,764	3,84	1,568						1	To mill remaining slanted faces
		3,3	6,5	0,435						1	To mill the punch
Slots	Rough and finish multiple slot end milling	0,492	1,25	0,742						4	W and D_1 are changed because of surface curvature
		1,63	12,5	0,375						1	
		0,25	1,379	0,25						1	
Holes	Drilling multiple holes				0,5	6,13				12	
					0,164	0,625				8	
					0,164	0,625				8	
	Drilling single hole				0,5	2,175				1	
					0,307	0,125				1	
					0,5	2,25				1	
					0,5	3,25				1	
	Counter-drilling single holes						0,125	0,063	1,8	1	
							0,125	0,063	0,76	1	
							0,125	0,063	0,93	1	
							0,125	0,063	1,55	1	
							0,875	0,414	0,563	1	
							0,414	0,307	0,187	1	
All machined features	Polishing and buffing	All machined surfaces									
All machined features	Inspecting visually	All surfaces of punch block									

Table 7 Features manufacturing data for cavity block

Features	Machining operation	Dimension (in)										Repeat count	Remarks
		W	L_1	D_1	D_2	L_2	D_3	d	L_3	A	D_4		
Faces	Rough and finish face milling	0,750	25	1,688								2	Calculated curvature surfaces are supposed to be neglected
Slots	Rough and finish multiple slot end milling	0,563	0,744	0,432								4	W and D_1 are changed because of surface curvature
	Rough and finish single slot end milling	0,25	5,348	0,25								1	
		0,188	7,878	0,125								1	
Holes	Drilling multiple holes				0,5	6,13						16	
					0,5	3,88						2	
					0,5	3,38						2	
					0,032	1,46						2	
					0,032	0,96						2	
					0,032	0,86						4	
	Drilling single hole				0,063	3,45						1	
					0,063	4,11						1	
					0,188	9,2						1	
					0,063	1,48						1	
					0,063	2,1						1	
					0,063	0,37						1	
	Counter-drilling single holes						0,125	0,063	2,95			1	
							0,125	0,063	3,61			1	
							0,33	0,19	0,46			1	
							0,405	0,332	0,27			1	
							0,332	0,188	0,46			1	
							0,125	0,063	1,13			1	
							0,125	0,063	1,75			1	
							0,125	0,063	0,56			1	
	Counter-drilling multiple holes						0,38	0,159	0,2			8	
							0,159	0,032	0,66			8	
Pocket	Rough and finish single pocket end milling									8,33	1,2	1	Concavity form is converted to standard geometry
	Polishing and buffing	All machined surfaces											
All machined features	Inspecting visually	All surfaces of the cavity block											

<u>DFM costing results:</u> The mould cost results obtained by DFM costing program for punch and cavity are presented in Table 8 and table 9 respectively.

Table 8 Punch block estimated costs

Process chart	Total cost per part ($)	Cost rate (%)
machining /cut from stock process	**1425,33**	100
Stock process	67,15	4,71
Worpiece	63,28	4,43
Abrasive cut off	3,87	0,27
Generic CNC machining center	**1167,5**	81,91
Set up/load/unload	86,96	6,1
Rough and finish face mill	631,96	44,33
Rough and finish multiple slot end mill	124,38	8,72
Drill single holes	23,39	1,64
Drill mutiple holes	270,07	18,94
Counterdrill single hole	25,05	1,75
Polish and buff	**183,56**	12,87
Inspect visually	**7,12**	0,5

Table 9 Cavity block estimated costs

Process chart	Total cost per part ($)	Cost rate (%)
machining /cut from stock process	**1467,45**	100
Stock process	53,88	**3,67**
Worpiece	50,02	3,4
Abrasive cut off	3,86	0,26
Generic CNC machining center	**1183,43**	**80,64**
Set up/load/unload	93,63	6,38
Rough and finish pocket end mill	149,07	10,15
Rough and finish face mill	84,15	5,73
Rough and finish single slot end mill	32,12	2,18
Rough and finish multiple slot end mill	34,22	2,33
Drill single holes	232,46	15,84
Drill mutiple holes	456,43	31,1
Counterdrill single hole	77,01	5,24
Counterdrill multiple holes	18,64	1,27
Polish and buff	**222,78**	**15,18**
Inspect visually	**7,36**	**0,5**

Note: the labor rate used in the software is Cad $75/hour

Concave mould costs breakdown: Figures 10 and 11 present respectively the costs breakdown for punch and cavity blocks of the concave mould.

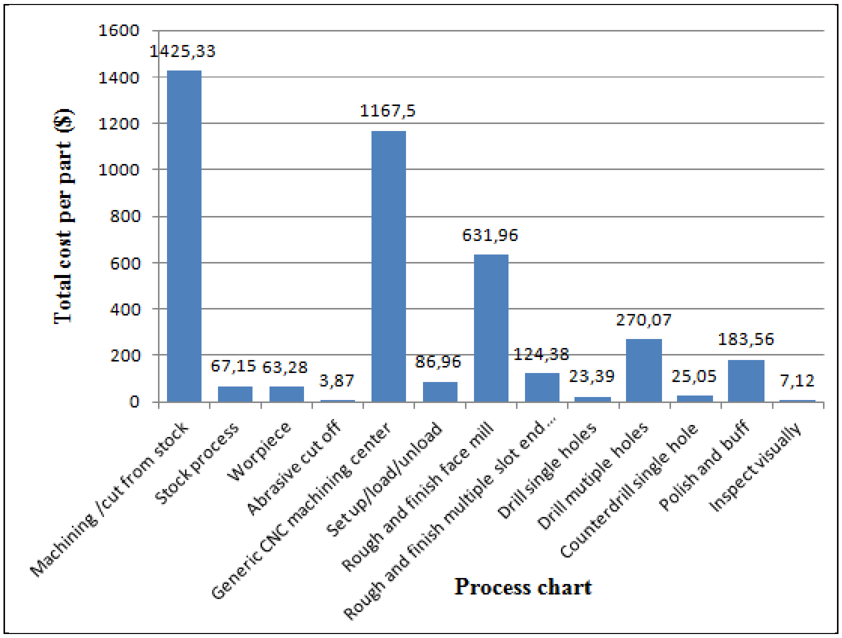

Figure 10 Breakdown of punch block costs

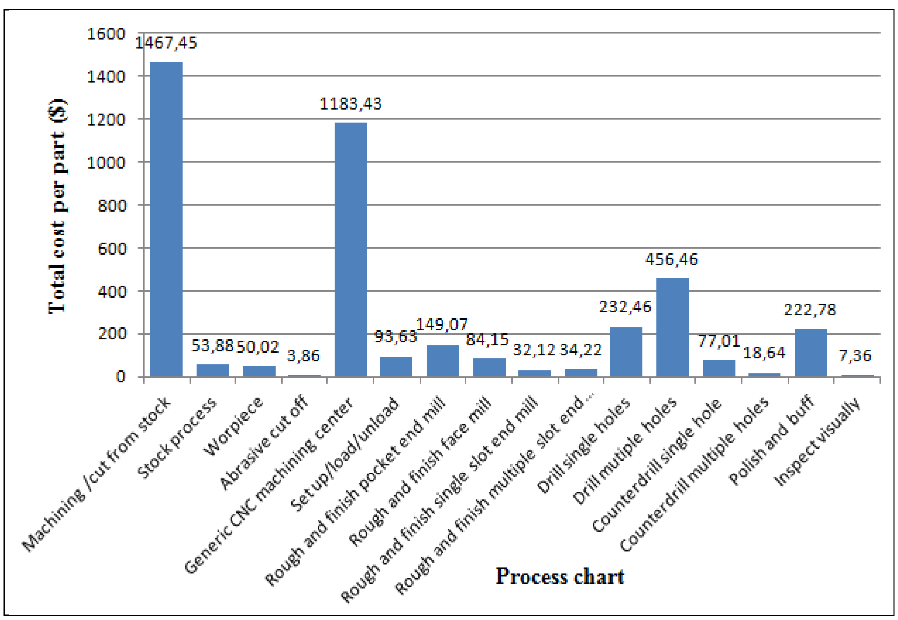

Figure 11 Breakdown of cavity block costs

Concave mould costs vs. production volume: (Figure 12)

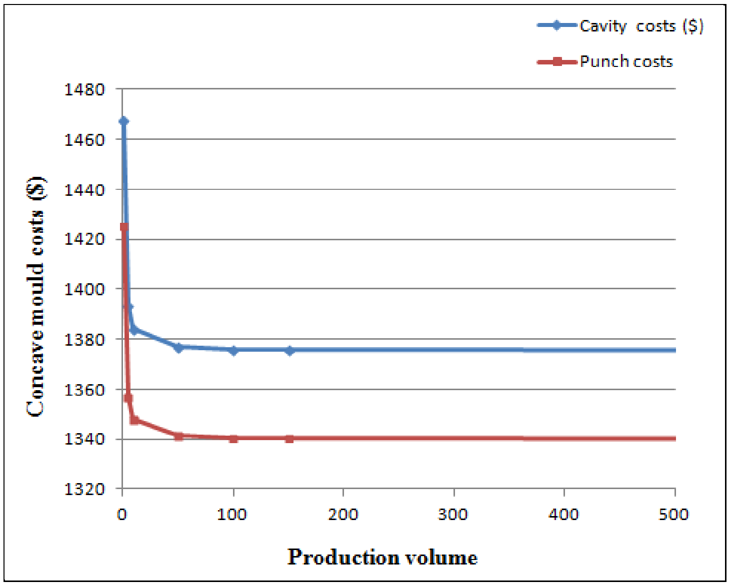

Figure 12 Concave mould costs vs. production volume

Side lock manufacturing processing: The manufacturing process is divided into two steps. The first step is to cut four parts from rectangular bar form stock. Each part is 1,625 inches long, 1,25 inches wide and 0,5 inches high. The second step is to cut and remove material from the parts. For making one side lock, it is needed to use face milling and two holes drilling operations. The figure 13 illustrates side lock design.

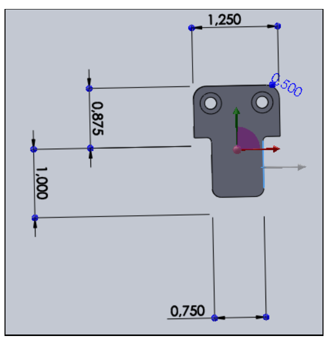

Figure 13 The side lock design

After machining operations, all the surfaces of the side locks are polished, and inspected afterward.

<u>Side lock features manufacturing data</u>: (Machined side lock volume: 0,75 in³)

In order to manufacture the side locks, the appropriate machining operations are selected for making the desired features (Table 11).

Table 11 Side lock features manufacturing data

Features	Machining operation	Dimension								Repeat count	Remarks
		W	L_1	D_1	D_2	L_2	D_3	d	L_3		
		In									
Faces	Rough and finish face milling	0,255	0,875	0,5	-	-	-	-		2	W is changed because of surface curvature
		0,05	0,15	0,5						2	Curvature form is converted to standard geometry
Holes	Drilling multiple holes	-	-	-	0,171	0,5	-	-		2	-
	Counter-drilling multiple holes						0,313	0,171	0,164	2	
All machined features	Polishing and buffing	All machined surfaces									
All machined features	Inspection visually	All surfaces of the part									

W: With of surface to be milled, L_1: Total length of surface to be milled (faces and slots), D_1: Total depth of material removed (faces and slots), L_2: Length of drilled holes, D_2: Diameter of drilled holes, L_3: Length to be counterdrilled, D_3: Diameter of counterdrill, d : Diameter of hole to be counterdrilled, A : Aera of pocket (in²), D_4 : Total depth of material removed from pocket

<u>Side lock costs breakdown:</u> (figure 14).

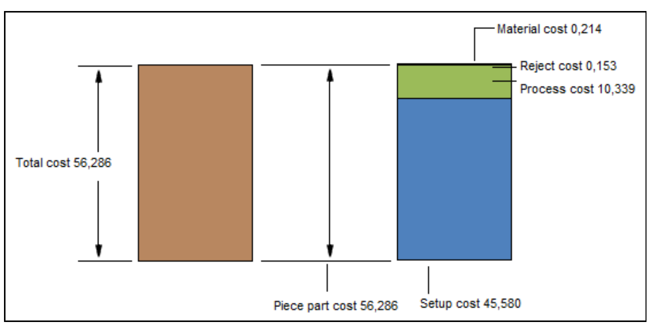

Figure 14 Side lock cost breakdown

<u>Mould base cost estimation:</u> Boothroyd et al (2002)[9] proposed a cost model for estimating the mould base costs in injection moulding process. This cost model can be

applied to the compression moulding process as well due to their similarity. The mould base costs can be estimated theoretically by Equation 2:

$$C_b = 1000 + 0{,}45\ A_c\ h_p^{\ 0{,}4} \quad \textbf{(2)}$$

where C_b is mould base costs ($), A_c is the area of mould base cavity plate (in^2) and is h_p the combined thickness of cavity and punch plate (in). In order to compare the quotations for the mould base to the theoretical costs, this formula needs to be adapted to the actual industrial Canadian costs by linear regression. Equation (3) and (4) permit to estimate the Canadian prices of the flat and concave mould bases respectively using 2013 Canadian industrial costs [10]. Table 12 presents mould base costs for different standard mould sizes [11] of both flat and concave geometries.

Table 12 Mould base costs [10, 11]

Mould base	Area (in^2)	h_p (in)	$A_c\ h_p^{\ 0,4}$	Canadian prices (2013)($)
Flat	15,875 x 20	2,375 x 2	592,13	5810
	15,875 x 23,5	2,375 x 2	695,75	6612
Concave	13,375 x 15	1,375 x 2	300,73	3942
	13,375 x 18	1,375 x 2	360,88	4456
	13,375 x 20,750	1,875 x 2	470,89	5296

$$C_b = 1239{,}78 + 7{,}72\ A_c\ h_p^{\ 0{,}4} \quad \textbf{(3)}$$

$$C_b = 1575{,}7 + 7{,}92\ A_c\ h_p^{\ 0{,}4} \quad \textbf{(4)}$$

<u>DFM and commercial cost estimation comparison for the concave part tooling</u>: (Table 10)

Table 10 DFM and commercial tooling cost estimation comparison

Item	DFM	Commercial
Mould costs	2892,78	-
Mould base	4564,66	--
Side locks	56,286	-
Manufacturing costs	7513,72	15145

4. Conclusion

For flat and concave moulds, the costs decrease when the production volume increases. There is no significant variation in term of mould costs along production series length. The threshold of the cost depends on each studied case. For flat mould the value is 100 components whereas it is approximately 1000 components for concave mould. Based on obtained cost results for the flat and concave mould by DFM costs estimating software, the mould costs extrapolation can be applied for other mould similar geometries by changing thickness or area of mould. In other cases the DFM program is able to estimate mould costs.

For the flat mould the costs estimated by DFM software are close to that of workshop except Nickel coating costs which cannot estimated by the DFM software. In the case of the concave mould, the cost results show a significant difference between costs estimated by DFM software and those of the commercial contractor. Keeping in mind that the commercial price of the concave mould comprised many elements such as taxes, shipping, labour rate, return on investment of the company etc…

The machining process is the most important cost driver in the cost analysis of two studied cases. The milling operations costs represent the highest cost rate because they depend on numbers and dimension of milled featured by considering that recommended milling parameters do not change.

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