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

Mohamed El Wazziki*, Anh Dung Ngo*, Gilbert Lebrun **, Hugues Lessard**

**Laboratoire de fabrication et de caractérisation de matériaux composites,*
Department of Mechanical Engineering, École de Technologie Supérieure,
1100 Notre-Dame ouest, Montréal, Québec, Canada, H3C-1K3
***Département de génie mécanique, Université du Québec à Trois-Rivières,*
3351, boul. des Forges, C.P. 500, Trois-Rivières (QC), Canada, G9A 5H7

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- ❑ Concave part

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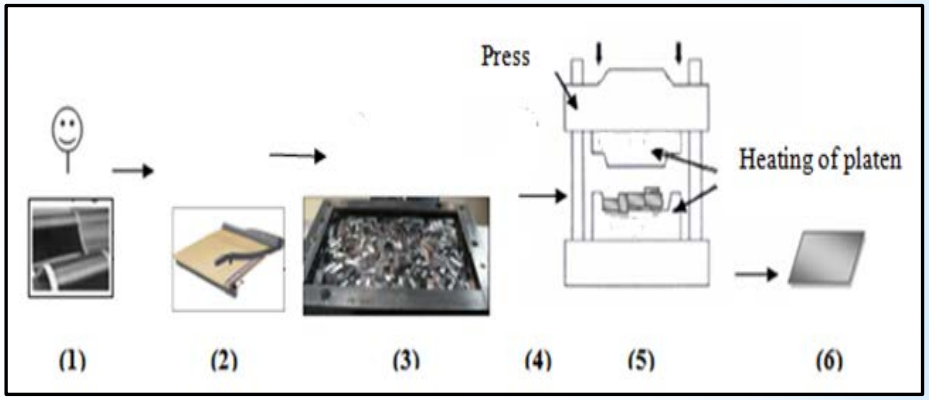
1. Introduction

- Carbon fibre reinforced thermoplastic composite has been an alternative to conventional materials in aerospace industry (major benefits)
- For the competitiveness , it is crucial to predict manufacturing costs of new product in design stage
- In research study a cost model has been developed to evaluate manufacturing costs of two types of parts (flat plate and concave part) made of carbon/PEEK by two compression moulding processes
- This study aims to use DFMA software of Boothroyd and Dewhurst Inc. to estimate the tooling costs for the parts made using these processes and to investigate the ability to extrapolate the moulds costs estimation to other part geometries

2. Composite parts manufacturing processing

Flat plate

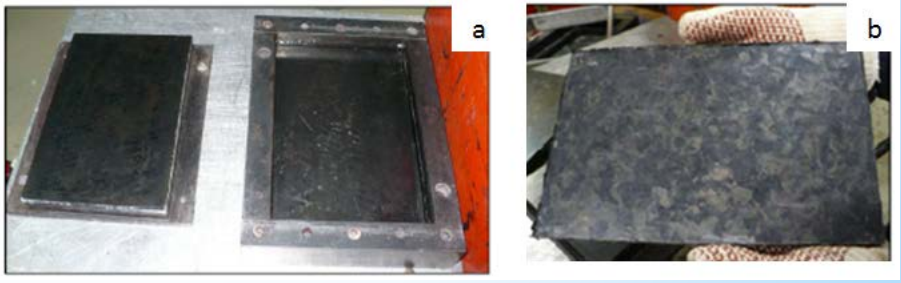
- Flat plate dimension: 280 mm x 185 mm x 6 mm
- AS4/PEEK UD prepreg tape dimension: W = 304.8 mm
- Strands dimension: 25.4 mm x 12.7 mm x 6 mm
- Flat plate manufacturing cycle:



(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

- Mould manufactured in IMI- NRC

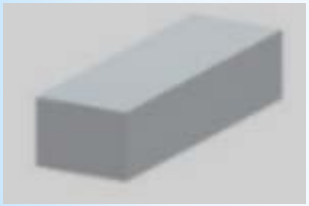
  Mould material: carbon steel P-20



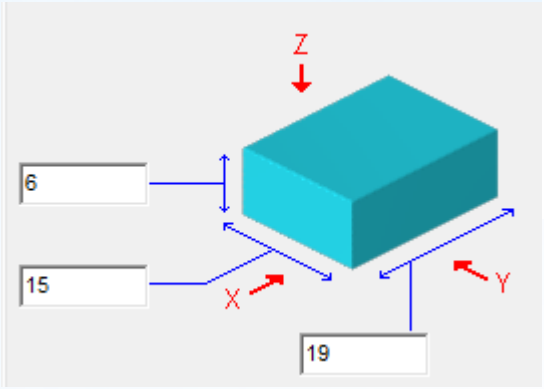
a) Two halves of the flat mould **b) manufactured flat plate**

a) Flat mould manufacture processing

1. Cut off from stock
2. Machining

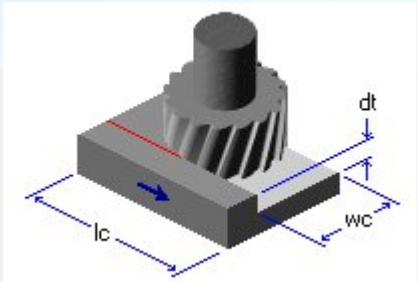


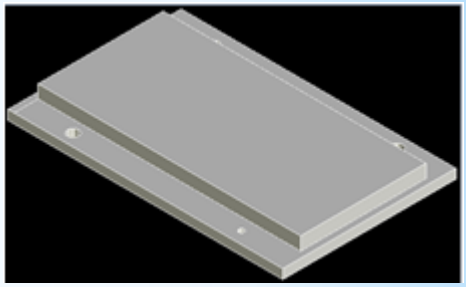
Rectangular bar stock



- Parts cut from stock
- Parts geometry import from solidworks to DFM program

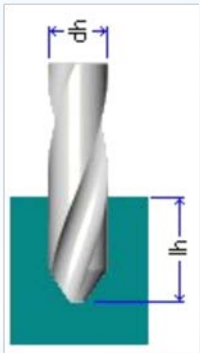
Face milling



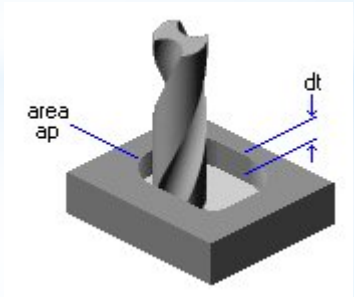


Punch

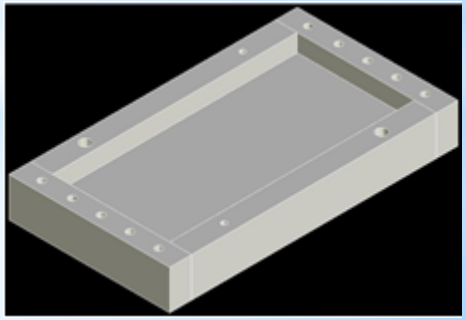
Holes drilling



(fixtures and thermocouples



Pocket milling



Cavity

Flat mould features 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	in²	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 =11x7 = 77 in²
	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								

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, A : Area of pocket (in²), D_4 : Total depth of material removed from pocket

b) DFM costing results

- Mould material is high carbon steel
- Labor rate used in the software is Cad $75/hour

Cavity block costs

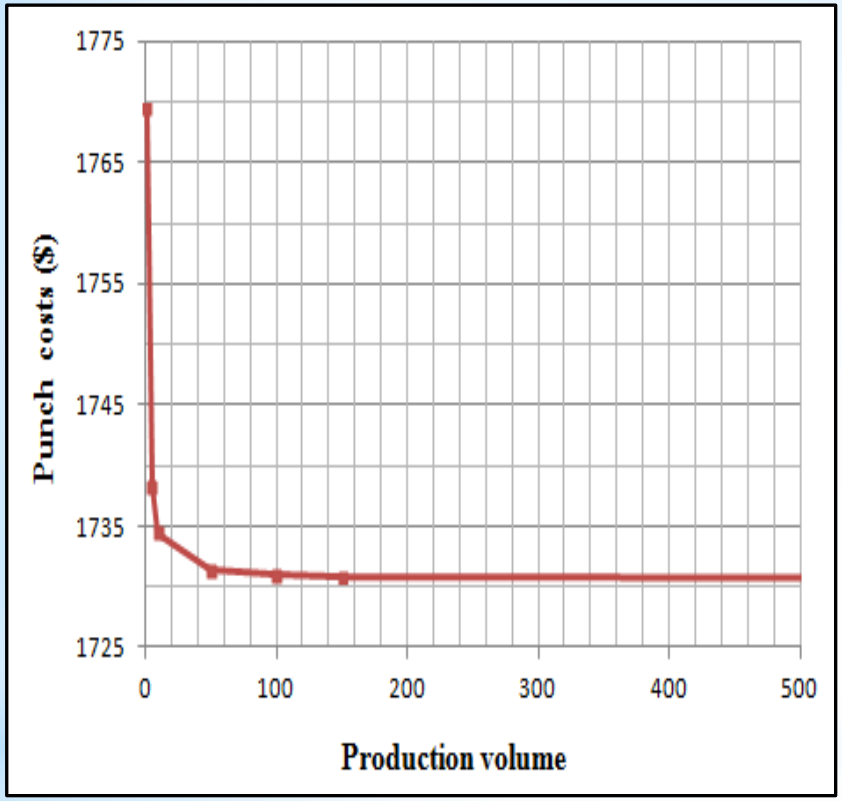
Process chart	Total cost par part ($)	Cost rate (%)
machining /cut from stock process	**1009,23**	100
Stock process	**272,62**	**27,01**
Worpiece	268,71	26,62
Abrasive cut off	3,92	0,38
Generic CNC machining center	**677,16**	**67,09**
Set up/load/unload	52,08	5,16
Rough and finish pocket end mill	584,79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

Punch block costs

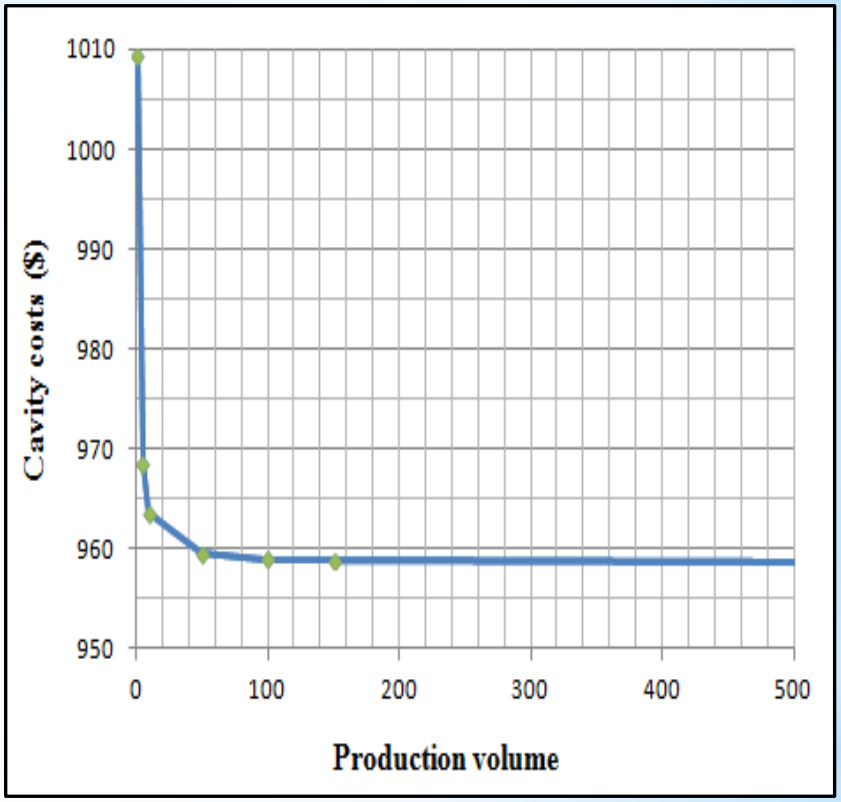
Process chart	Total cost par part ($)	Cost rate (%)
machining /cut from stock process	**1769,5**	100
Stock process	**272,62**	**15,4**
Worpiece	268,71	15,18
Abrasive cut off	3,92	0,22
Generic CNC machining center	**1429,73**	**80,79**
Set up/load/unload	40,23	2,27
Rough and finish face mill	1367,12	77,26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

Flat mould costs vs. mould production volume

Punch block



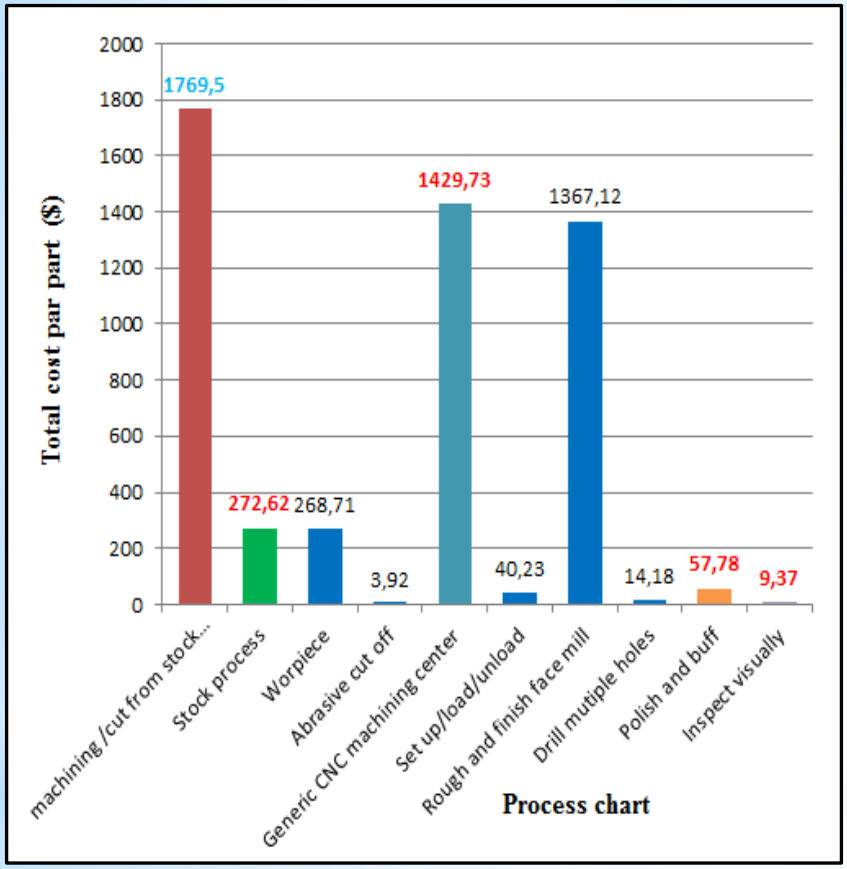
Cavity block



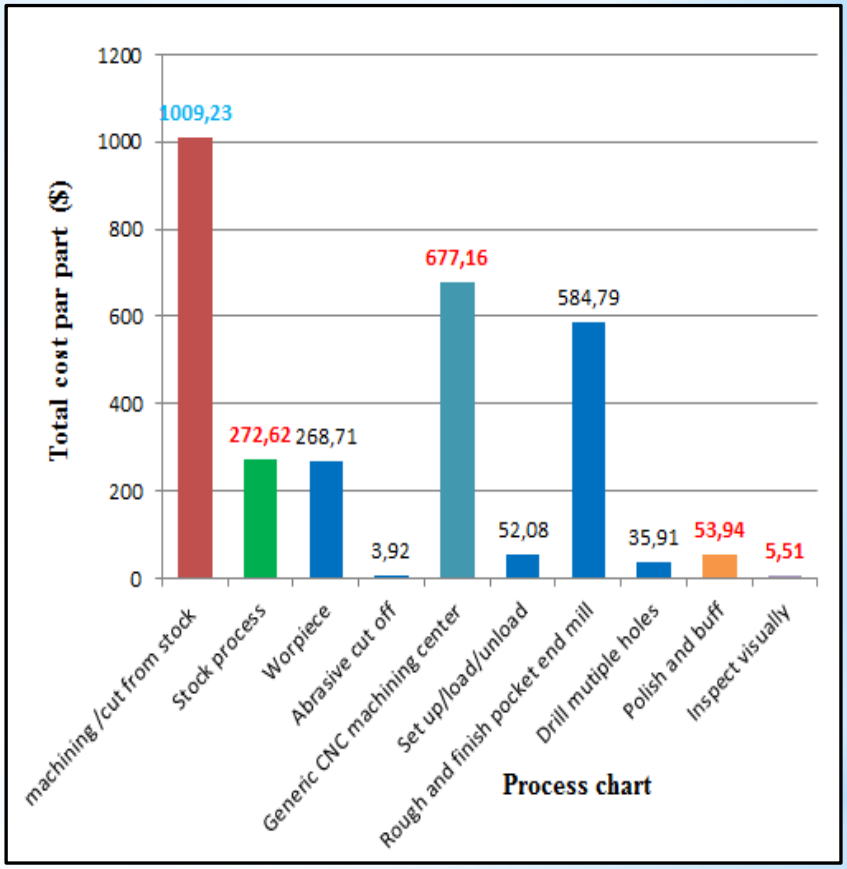
- Starting from 100 components there is no variation of mould costs. There is approximately 50$ of costs reduction.
- Consequently, composites parts production volume does not have a significant effect on the mould costs.

Flat mould costs breakdown

Punch costs



Cavity costs



- The total cost per part is strongly dominated by the machining costs of two studied cases due to highest rate of milling costs
- The Machining costs for the punch are higher than for the cavity due to higher time to machine the great features geometry made in punch

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DFM and workshop tooling cost estimation comparison

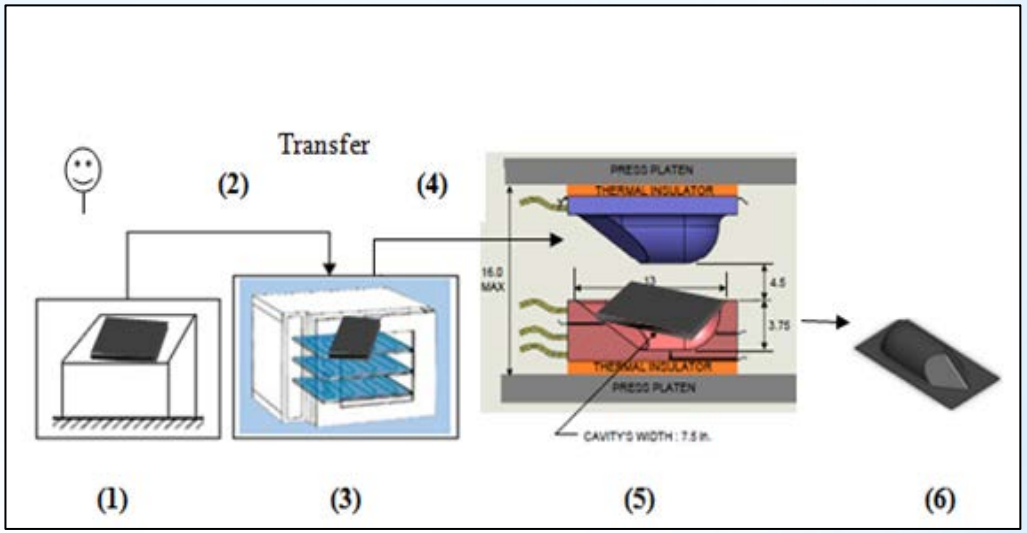
Item	DFM	Workshop
Material costs ($)	542,82	540,00
Manufacturing costs($)	2235,91	2325,00
Nickel coating ($)	-	600,00

- The flat mould the costs estimated by DFM software are close to that of workshop except Nickel coating costs which cannot be estimated by the DFM software

2. Composite parts manufacturing processing

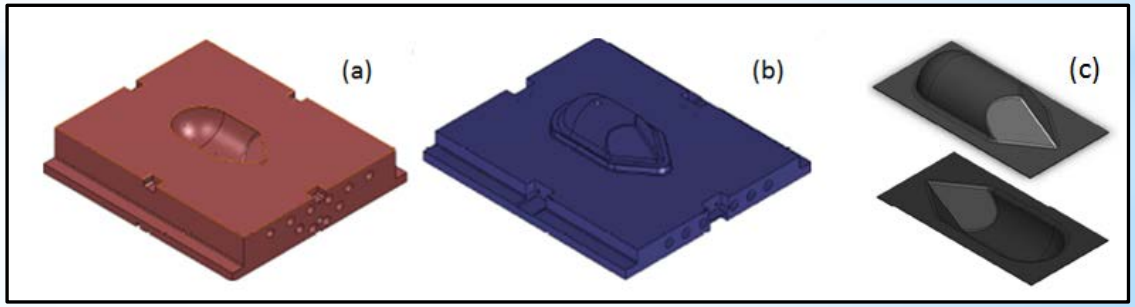
Concave part

- Concave part dimension: 6 mm x 152.4 mm x 4 mm
- Material: laminate of continuous fibre prepreg plies of carbon/PEEK
- Concave part manufacturing cycle:



(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

- Mould manufactured by PCM Innovation company, contractor of UQTR



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

a) Concave mould manufacture processing

Cut off from stock

Rectangular bar stock

Two parts cut from stock

Machining

Milling

Faces, slots, pocket, punch

Drilling

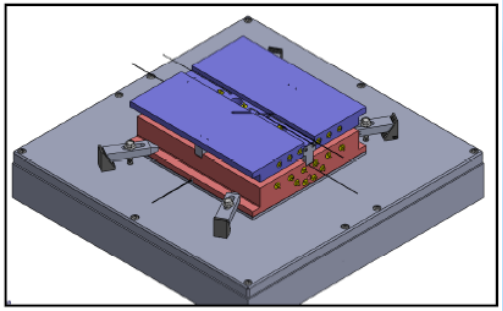
Holes

Parts geometry import from Solidworks to DFM program

Polishing and buffing

Inspection

Mould assembly



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Features manufacturing data

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									

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,

Features manufacturing data

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 machi-ned features	Inspecting visually	All surfaces of the cavity block											

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

b) DFM costing results

- Mould material is high carbon steel
- Labor rate used in the software is Cad $75/hour

Punch block costs

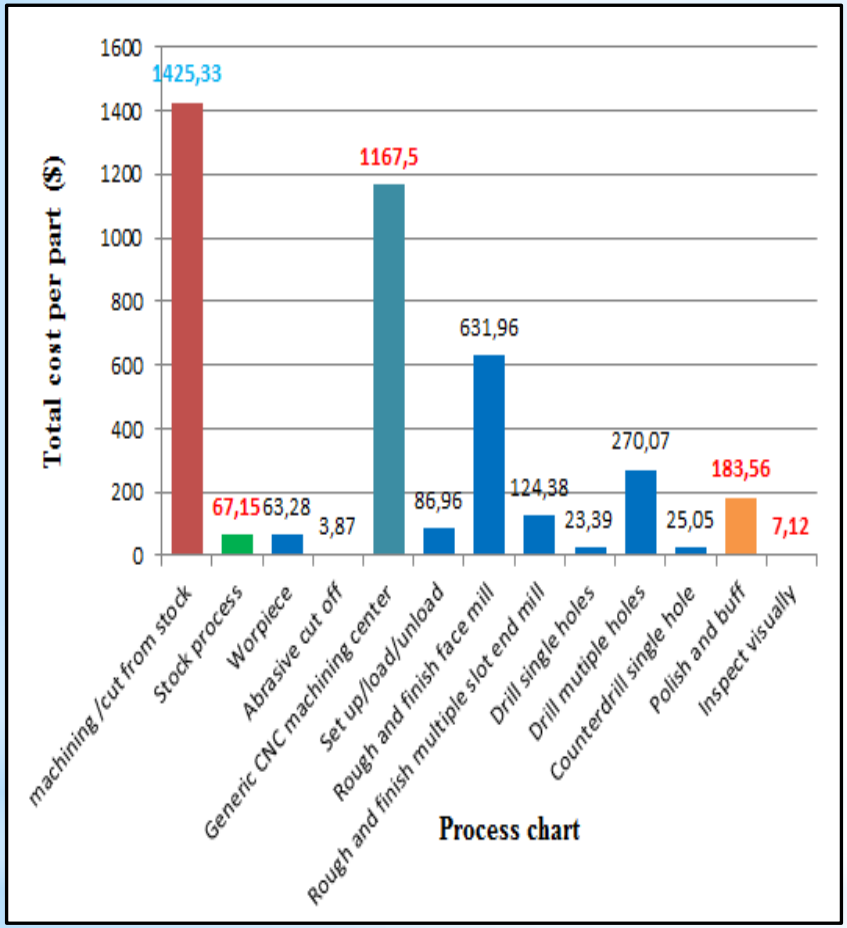
Process chart	Total cost per part ($)	Cost rate (%)
machining /cut from stock process	**1425,33**	100
Stock process	67,15	**4,71**
Worpiece	63,28	4,43
Abrasive cut off	3,87	0,27
Generic CNC machining center	**1167,5**	**81,91**
Set up/load/unload	86,96	6,1
Rough and finish face mill	631,96	44,33
Rough 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**

Cavity block costs

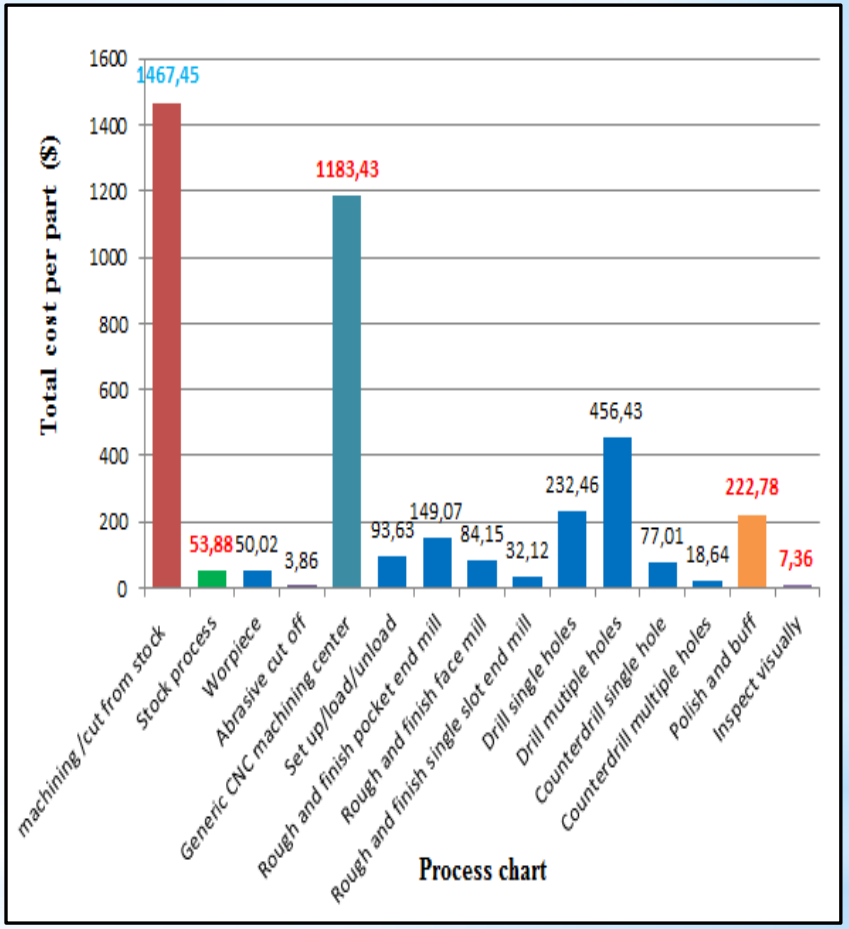
Process chart	Total cost per part ($)	Cost rate (%)
machining /cut from stock process	**1467,45**	100
Stock process	53,88	**3,67**
Worpiece	50,02	3,4
Abrasive cut off	3,86	0,26
Generic CNC machining center	**1183,43**	**80,64**
Set up/load/unload	93,63	6,38
Rough and finish pocket end mill	149,07	10,15
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**

Concave mould costs breakdown

punch block costs

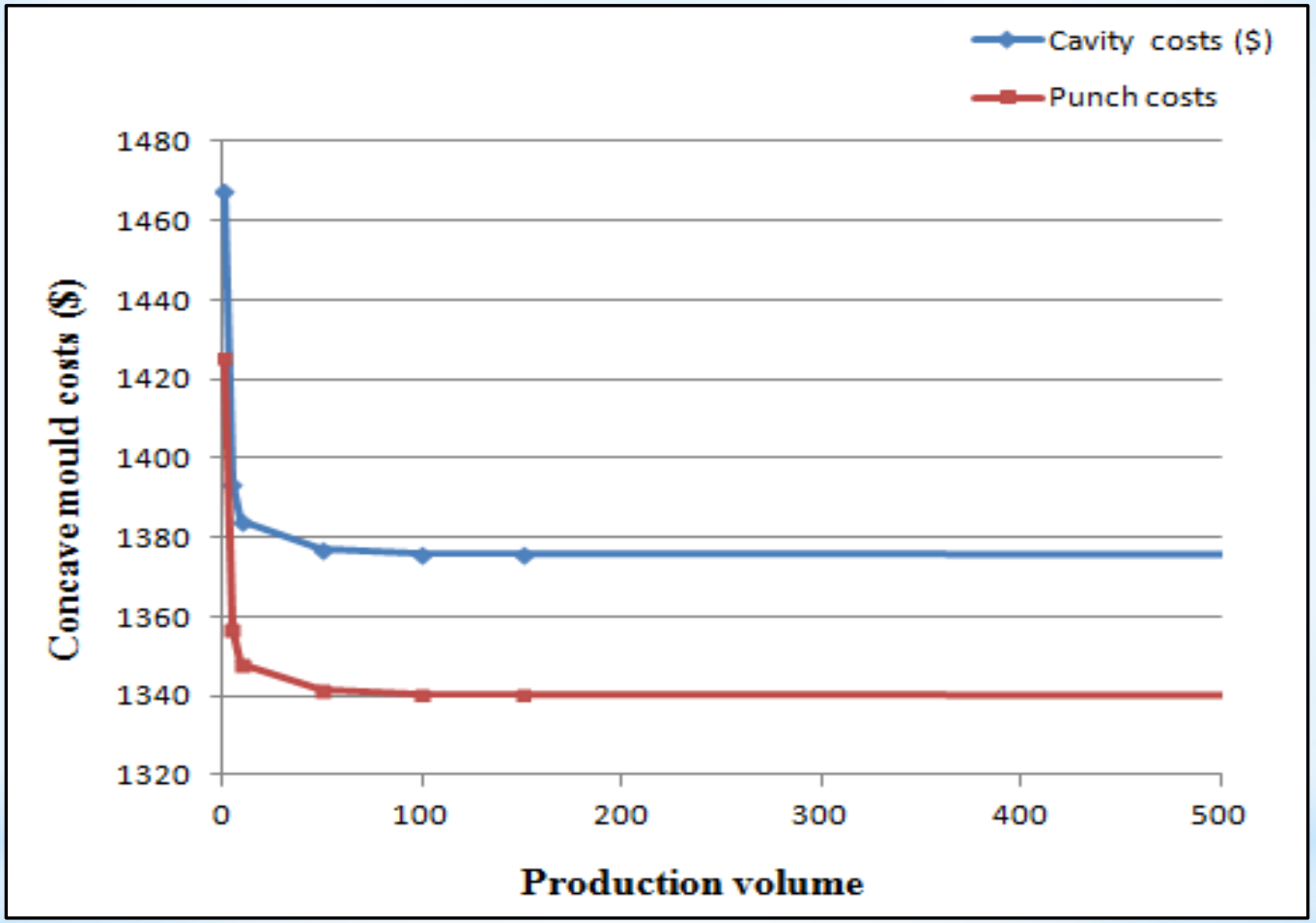


Cavity block costs



- The total cost per part is strongly dominated by the machining costs of two studied cases due to highest rate of milling costs
- The Punch machining costs are close to that of the cavity due to the approximate machining time between them

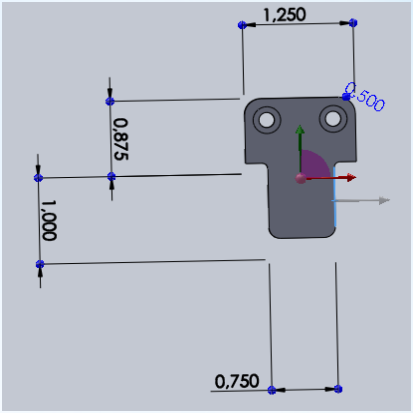
Concave mould costs vs. production volume



- Starting from 100 components there is no variation of mould costs. There is approximately 50$ of costs reduction.
- Consequently, composites parts production volume does not have a significant effect on the mould costs.

Side lock manufacturing processing

- 4 Parts dimension cut from stock (in): 1,625 x 1,25 x 0,5
- 2 faces milling and 2 holes drilling operations
- Side lock material: carbon steel H -13

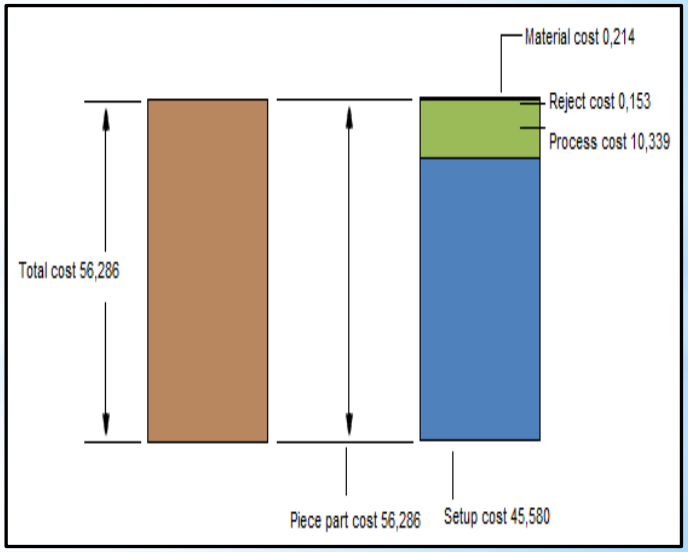


The side lock design

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									

Side lock costs breakdown



Mould base cost estimation

- The mould base costs can be estimated theoretically by Boothroyd and als:

$$C_b = 1000 + 0{,}45\, A_c\, h_p^{\,0,4}$$

- For comparaison of the quotations for the mould base to the theoretical costs, this formula is adapted to the actual industrial Canadian costs by linear regression
- Using mould base costs for different standard mould sizes of both flat and concave geometries.

C_b is mould base costs ($),
A_c is the area of mould base cavity plate (in^2)
h_p the combined thickness of cavity and punch plate (in)

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

- Mould base Canadian prices are estimated by:

$$C_b = 1239{,}78 + 7{,}72\, A_c\, h_p^{\,0,4}$$

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

DFM and commercial cost estimation comparison for the concave part tooling

Item	DFM	Commercial
Mould costs ($)	2892,78	-
Mould base ($)	4564,66	--
Side locks ($)	56,286	-
Manufacturing costs ($)	**7513,72**	**15145,00**

- The cost results show a significant difference between costs estimated by DFM software and those of the commercial contractor.
- The commercial price of the concave mould comprised many elements such as taxes, shipping, labour rate, return on investment of the company, etc…

3. Conclusion

- For flat and concave moulds, costs decrease with increasing mould production volume
- The threshold of the moulds costs is approximately 100 components
- Due to the highest cost rate of the milling operations, the machining cost is the most important cost element in the total costs for the two studied cases
- For the flat mould, the costs estimated by DFM software are close to that of internal workshop except Nickel coating costs which cannot estimated by the DFM software
- For the concave mould, the cost results show a significant difference between the costs estimated by DFM software and those of the commercial contractor
- The obtained cost results for the flat and concave moulds by DFM costs estimating software can be extrapolated for other similar mould geometries.

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- Bombardier Inc.
- Pratt and Whitney Canada Corp.
- Marquez Transtech Ltd.
- Delastek Inc.
- Avior Integrated Products Inc.