DIMENSIONAL CAPABILITY OF CARBON FIBER REINFORCED EPOXY EXTERIOR AUTOMOTIVE PRODUCTS

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Abstract

As automakers continue in their efforts to reduce overall vehicle mass, light weight, high strength materials such as composites figure to gain wider acceptance for use in mainstream, high volume vehicles. Vermont Composites, Inc. (VCI) has partnered with General Motors to implement the automotive industry's highest known volume usage of carbon fiber reinforced exterior body panels. VCI is the exclusive supplier to GM for the carbon fiber reinforced front fenders utilized on the 2006 Corvette Z06. The fenders are constructed of uni-directional carbon fiber reinforced epoxy resin, with a nominal thickness of 1.2mm and a nominal mass of 3.5 pounds (before paint).

Dimensional topics to be discussed include a general overview of the part-dimensioning scheme, gage design, the process of validating gage repeatability (Gage R) and gage repeatability and reproducibility (Gage R&R), and inspection techniques.

This paper will summarize the work performed to date in the design and development process with respect to dimensional capability of the fenders. Product design topics such as localized product cross-section, fiber orientation, balancing, symmetry, and localized reinforcing will be discussed. Impacts of these various design and development items will be addressed using information collected during ongoing product inspection capability studies.

Introduction

The front fenders for the 2006 Corvette Z06 are produced using unidirectional carbon fiber reinforced epoxy. Originally the fenders were designed a prototyped (BETA) at 0.8 mm thick or 4 plies of 190 gm/m2 unidirectional prepreg with a fiber orientation of (0/90/90/0). Later in the vehicle validation process the platform determined that the fenders were overly prone to oil canning due to being a little too thin. The lamination was increase to 6 layers or 1.2 mm nominal thickness. The area of the fender below the gill, more commonly referred to as the rocker area of the fender remains at 0.8 mm. Build issues associated with dimensional variation, especially in the body structure require the fender to be more flexible in select spots. In effect, fit variation not necessarily due to issues with the fender is chased to below the door line.

Many of the very thin areas along the outside edges of the part required beefing up in order to stiffen the part and improve flushness and gap measurements to the Headlamp and Door. This thickness increase had to remain a balanced and symmetrical fiber orientation as we discovered the edges tended to curl or distort when the thickness build-up was highly oriented, i.e. all 0's or all 90's. We also determined that along the door edge above the gill opening we had to step the thickness down gradually, like the steps of stairs in 10mm increments in order to reduce read through and the subsequent effect on Class A surface finish.

Many lessons were learned relative to Class A surface finish using unidirectional carbon fiber reinforced epoxy, these lessons may be reviewed another day in a different technical presentation.

The molds were inherited for BETA are produced in INVAR and are extremely heavy and difficult to work with. The current production molds are produced from forged billets of high chrome (P-20) steel. The coefficient of thermal expansion of the P-20 steel forced us to design the molds with a shrinkage factor. This shrinkage factor wouldn't have been required with INVAR, but P-20 is quite a bit harder to scratch and has a significantly better heat coefficient than the INVAR. Also, large forged billets of INVAR were unavailable and prohibitively expensive. The team elected to go with forged billets after an encounter with casting porosity in a nearly finished mold. The tooling design team was exceptionally careful to manage mass for optimized heat transfer. We also designed unique and low mass vacuum chucked easy to handle and simply removable inserts for the areas of the fender that are die locked. It is important to note that all of the primary datum surfaces are located in these die locked areas, which required removable inserts. The consistent positioning of the inserts is critical to the dimensional repeatability of the fenders. At this time, we are not going to go much more than this into mold design. Refer to Figure #1 for a picture of a typical P-20 steel mold with removable inserts.

Part Design

The carbon fiber reinforced epoxy fender is nominally 1.2 mm thick with areas below the rocker at 0.8 mm. Initially the fender was produced with an over all thickness of 0.8mm, but the thickness was increased due to a concern of oil canning in the field.

The nominal lamination uses 6 layers of unidirectional material oriented 0,90,0,0,90,0 with the zero (0) direction being fore/aft and the (90) direction being cross car.

Thickness control of the structural composite was of major concern given the application requirements for fit and finish and the customer's requirement for a process capability of 1.333 PPK. The composite material is nominally 190 +/- 7.5 gm/m2 carbon fiber and has 38% +/- 3% resin. The material normally molds at ~0.2 mm per ply, 6 plies thick = 1.2 mm. The molding process utilizes a vacuum bag for applying pressure to the backside of the part. Uniformity of the backside of the part was a major concern given that it is these areas the fender mates to the car and is the primary up/down datum surfaces in the GD&T.

The part is die locked on all four sides. The entire length of the catwalk required two interlocking removable inserts. The return flange in the door opening for attaching the fender to the door H-pillar curls back on itself almost 180 degrees. There is another z-shaped return flange on the fender outside of the headlamp for attachment to the composite headlamp support structure. Finally, the bottom of the rocker turns back on itself requiring another removable insert. All of these surfaces contain one or more of the primary up/down or cross car datum planes.

Many of the return flanges are significantly thicker than 1.2 mm; most are increased to at least 2.0 mm. This thickness increase was executed by adding balanced orientation strips of unidirectional prepreg to the return flanges.

One of the biggest development efforts was in the engineering of all of the ply slices and overlaps. These we tried to place in the tight radii near the return flanges or if forced to place them on a class A surface we moved them over the highly contoured surfaces in order to disguise the effect on the Class A finish. The biggest issue was in controlling or managing the changes in fiber orientation as the lamination transitioned the complex surfaces. VCI Engineering initially adopted a +/- 5^{o} fiber orientation in the nesting process, this proved to be too much of a disruption in component fiber balance resulting in unacceptable dimensional results. For the primary plies of the fender (4) pieces, we keep the fiber orientation under very tight control. We have found that for the secondary plies the 5-degree variation is acceptable at this time. These multilayers plies are all CAD designed and then cut on a CNC material cutting machine. It is very common for us to preply the unidirectional prepreg prior to cutting the shapes in order for us to reduce ply count. Also, the unidirectional prepreg behaves much like a plain weave fabric when preplied. It is nearly impossible to laminate unidirectional prepreg over complex contoured surfaces using single layers of unidirectional prepreg.

Figure 1: Typical Fender mold showing removable inserts

Geometric Dimensioning and Tolerance Scheme

The predominate datum planes coincide with the surfaces the fender attaches to the vehicle, up/downs (A1 – A9) are predominately along the hood line/cat walk but there is one at the bottom of the rear edge of the rocker and another on the bottom of the z-bracket by where the fender attaches to the composite headlamp support reinforcement. Cross car control of the part begins at the rear of the catwalk (-B-) a 4.2 mm hole and at the front of the catwalk (-C-) a 10.0 mm hole, there are three other cross car locating datum's, (-D-) a 12.0 X 14.0 slot on the door H-pillar attachment flange, (-E-) a 8.0 X 14.0 slot at the rear edge of the rocker and (-G-) a 6.7 X 9.2 mm slot on the z-bracket. The primary fore/aft is at the rear of the catwalk at the 4.2 mm hole, other fore/aft datum's are at the (-E-) 8 X 14 mm slot at the rear edge of the rocker and the (-G-) 6.7 X 9.2 mm slot on the z-bracket.

Pinning the fender for positive location was an issue as it is not normal to mold holes using unidirectional carbon/epoxy. Only one hole is molded into the fender, the primary 4.2 mm fore/aft and cross car locator. The remainder of the locating holes and slots in the GD&T are machined using a 6-axis robot.

The dimensional tolerance for surfaces is +/- 0.75 mm for flushness and gap to the hood, doors, headlamps and the front fascia, shown in sections A-A, B-B, C-C and D-D

There are 28 Process Measurement Points defined for Statistical Process Control. These PMP's reflect flushness and gap requirements along the hood line, door line, headlamp and front fascia. These PMP tolerances are +/- 0.75 mm. It is the intent of this paper to present how Vermont Composites has been able to conform to these requirements. Refer to figures 2,3 &4 for clarification of GD&T requirements.

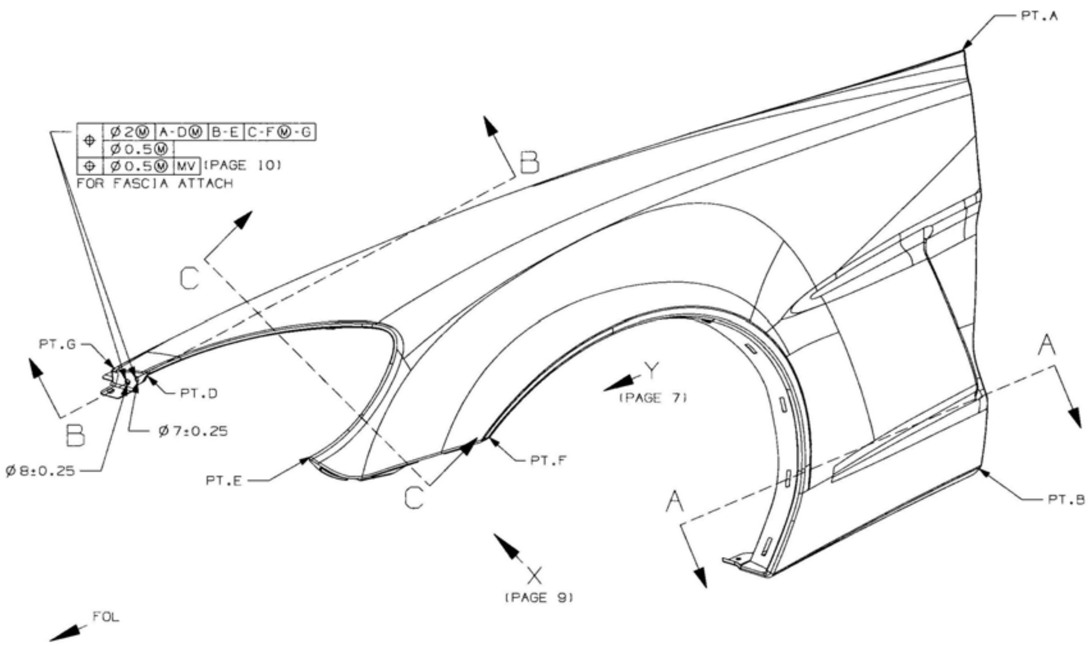

Figure 2: GD&T detail showing section locations

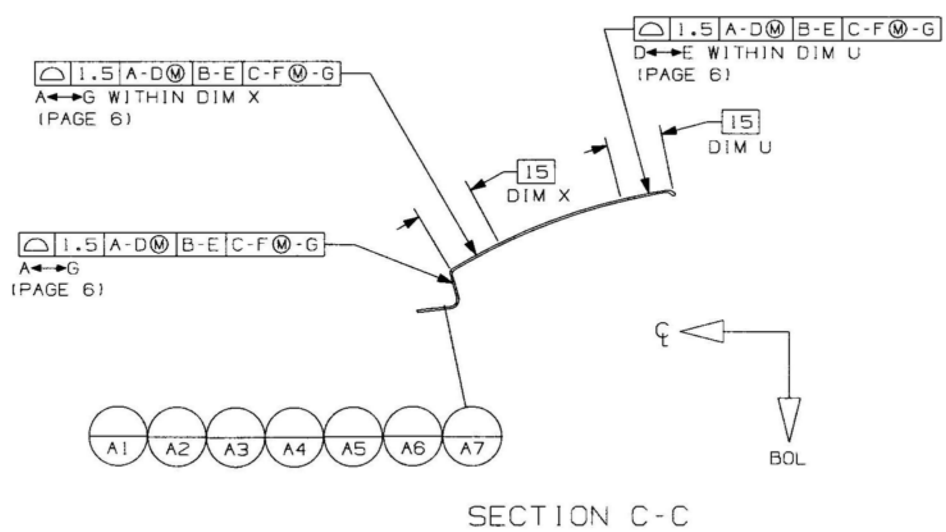

Figure 3: GD&T surface tolerance call out (easy)

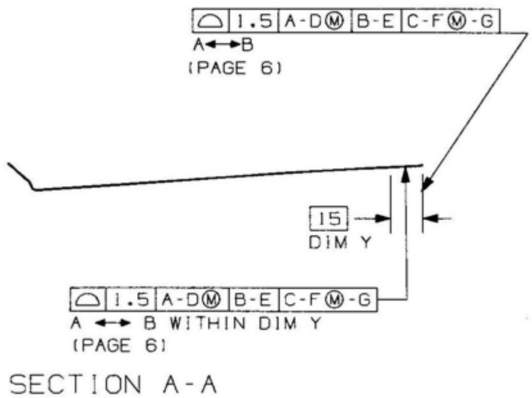

Figure 4: GD&T surface tolerance call out (hard)

Robot Machining Fixture Design

The machining fixture is a machined female surface nest with suction cups pulling the part into the fixture. Biggest issue in the design was to handle the die locked return flanges at the door-opening, fascia attach and the bottom surface at the rocker. It was especially concerning because there are datum holes/slots in the rocker, fascia z-bracket and door opening attachment flange. Because of these critical holes the routing fixture design was driven to have pneumatically operated linear actuators again with suction cups pulling that section of the fender into the surface conforming nest. Refer to figure #5 for a picture of a typical routing fixture.

Vermont Composites initially investigated water jet cutting of the fender, but it was quickly decided that the part was too complex to cost effectively machine using this technology. It was also concluded that simple water jet would not pierce the holes without minor amounts of delaminating and that abrasive slurry would be required.

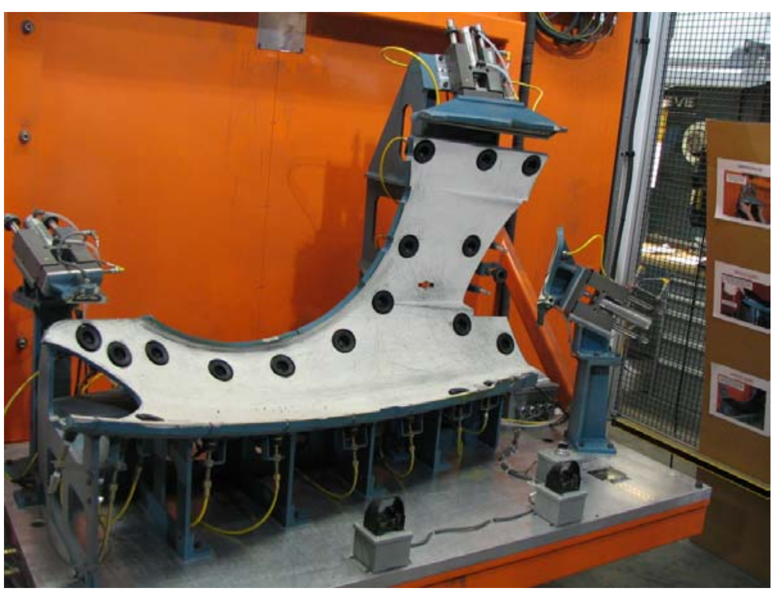

Figure 5: Routing fixture for LH fender

Gage Design

The volume of fenders required by General Motors did not justify the use of an automated data collection design. Instead Vermont Composites decided to use a manual system using a digital dial indicator with fixed drill bushings on swing in/out details. This created issues with gage repeatability and used valuable variation up in the gage reliability and repeatability studies. Refer to figure #6 for a picture of a typical inspection gage.

Figure 6: Inspection Gage for RH fender

Gage Repeatability

One inspector conducts Gage repeatability measurements. The inspector measures the same part 10 times using exactly the same procedure. Total variation permitted cannot use more than 18% of the total tolerance at ~5 Sigma. Vermont Composites had difficulty achieving an acceptable Gage Repeatability in the relatively thin areas around the headlamp opening and below and above the gill opening along the door line. Refer to figure #7 for an example of a typical worksheet for gage repeatability.

Gage Repeatability and Reproducibility

Gage R&R measurements were conducted by 2 inspectors. These inspectors each measured the same 3 parts five (5) times. There are 28 PMP locations specified and the total tolerance (TT) used by the gage in order to conform to General Motor's specifications cannot exceed 30% of the requirement. In our case, on average we were able to keep the TT below 10%. Again the difficult to control points around the thin unsupported areas of the headlamp, above and below the gill opening along the door line. Refer to figure #8 for an example of a typical Gage R&R worksheet.

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Gage Repeatability Study Worksheet

(one part ten times by one operator)

1 X 10

Gage Number:		**Part Number:**	*AKJ 67500 LEFT HAND*
Gage Cert. Level:		**Part Name:**	*FRONT FENDER ASM.*
Gage Cert. Date:		**Part Drawing No.:**	
Gage Build	*MODELS & TOOLS*	**Dwg LEC:**	**Math LEC:**
Operator:	*ARNIE*	**Date of check:**	*01-Jul-05*

O.P. Check Point	1	2	3	4	5	6	7	8	9	10	11
*** % of GRE GRE X 100/TOL	2.83	3.32	9.58	4.14	10.00	14.83	7.20	17.61	15.10	14.84	6.63
Pass / Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Tolerance +	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Tolerance -	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Reading 1	-0.05	0.19	-0.02	0.31	-0.04	-0.12	0.19	0.06	0.74	0.31	-1.80
Reading 2	-0.06	0.19	-0.04	0.30	-0.05	-0.16	0.18	0.01	0.72	0.22	-1.80
Reading 3	-0.07	0.19	-0.05	0.30	-0.08	-0.17	0.17	-0.02	0.70	0.25	-1.79
Reading 4	-0.06	0.17	-0.06	0.30	-0.08	-0.14	0.18	0.03	0.74	0.25	-1.81
Reading 5	-0.05	0.19	-0.04	0.30	-0.04	-0.15	0.20	0.05	0.76	0.25	-1.81
Reading 6	-0.07	0.19	-0.04	0.32	-0.07	-0.19	0.17	-0.01	0.70	0.21	-1.77
Reading 7	-0.05	0.19	-0.06	0.32	-0.08	-0.20	0.15	-0.03	0.69	0.21	-1.79
Reading 8	-0.05	0.17	-0.07	0.30	-0.06	-0.17	0.19	0.02	0.74	0.27	-1.81
Reading 9	-0.05	0.19	-0.01	0.30	-0.03	-0.13	0.16	0.02	0.67	0.21	-1.79
Reading 10	-0.06	0.17	-0.11	0.28	-0.13	-0.27	0.13	-0.12	0.61	0.15	-1.75
Maximum	-0.05	0.19	-0.01	0.32	-0.03	-0.12	0.20	0.06	0.76	0.31	-1.75
Minimum	-0.07	0.17	-0.11	0.28	-0.13	-0.27	0.13	-0.12	0.61	0.15	-1.81
RANGE (R)	0.02	0.02	0.10	0.04	0.10	0.15	0.07	0.18	0.15	0.16	0.06
*Std Dev	0.01	0.01	0.03	0.01	0.03	0.04	0.02	0.05	0.04	0.04	0.02
**GRE Std Dev X 5.15	0.04	0.05	0.14	0.06	0.15	0.22	0.11	0.26	0.23	0.22	0.10
TOL +/- to achieve <18%	0.12	0.14	0.40	0.17	0.42	0.62	0.30	0.73	0.63	0.62	0.28

*Sample Standard Deviation
* * Gage Repeatability Error
* * * Percent of Gage Repeatability Error

Remarks:

Percent of gage repeatability error (% of GRE) is based on 10 measurements per PMP point using the following formula: s X 5.15 X 100/total tolerance = % of GRE.

Std. Dev. $s = \sqrt{\dfrac{\sum (x - \bar{x})^2}{n-1}}$

Figure 7: Gage Repeatability Worksheet

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET
DATA RESULTS

Part Number: 10327646		Gage Name: Left Hand Fender	Appraiser A: Heath Murphy	
Part Name: Left Hand Fender		Gage Number: 10327646	Appraiser B: Marty Hoffman	
Characteristic: PMP 14	Total Tolerance: 1.500	Gage Type:	Appraiser C:	
Characteristic Classification:		Trials: 3 / Parts: 5	Appraisers: 2	Date Performed: 23-Mar-05

APPRAISER/ TRIAL #		295	296	297	294	299	6	7	8	9	10	AVERAGE	
1. A	1	0.180	0.070	0.330	0.230	0.280							0.218
2.	2	0.150	0.070	0.350	0.270	0.250							0.218
3.	3	0.160	0.080	0.330	0.250	0.260							0.216
4.	AVE	0.163	0.073	0.337	0.250	0.263						X_a=	0.217
5.	R	0.030	0.010	0.020	0.040	0.030						r_a=	0.026
6. B	1	0.240	0.070	0.320	0.280	0.230							0.228
7.	2	0.150	0.100	0.420	0.290	0.260							0.244
8.	3	0.130	0.090	0.320	0.270	0.250							0.212
9.	AVE	0.173	0.087	0.353	0.280	0.247						X_b=	0.228
10.	R	0.110	0.030	0.100	0.020	0.030						r_b=	0.058
11. C	1												
12.	2												
13.	3												
14.	AVE											X_c=	
15.	R											r_c=	
16. PART AVE (Xp)		0.168	0.080	0.345	0.265	0.255						X= / R_p=	0.223 / 0.265
17.	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0.042
18.	(Max X - Min X) =											X_{DIFF}=	0.011
19.	R x D_4* =											UCL_R=	0.108

GAGE REPEATABILITY AND REPRODUCIBILITY REPORT
ANALYSIS OF DATA

Part Number: 10327646		Gage Name: Left Hand Fender	Appraiser A: Heath Murphy	
Part Name: Left Hand Fender		Gage Number: 10327646	Appraiser B: Marty Hoffman	
Characteristic: PMP 14		Gage Type:	Appraiser C:	
Characteristic Classification:		Trials: 3 / Parts: 5	Appraisers: 2	Date Performed: 23-Mar-05

Measurement Unit Analysis						% Total Var (TV) & Total Tol (TT)		
Repeatability - Equipment Variation (EV)						% EV	=	100 (EV/(TOL/6))
EV	=	R x K_1		**Trials**	**K1**		=	100(0.025/0.250)
	=	0.042 x 0.5908		2	0.8862		=	9.93
	=	0.025		3	0.5908	% AV	=	100 (AV/(TOL/6))
Reproducibility - Appraiser Variation (AV)							=	100(0.004/0.250)
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$					=	1.59
	=	{(0.011 x 0.7071)^2 - (0.025 ^2/(5 x 3))}^1/2				% GRR/TV	=	100 (GRR/TV)
	=	0.004	**Appraisers**	**2**	**3**		=	100(0.025/0.110)
n = parts	*r = trials*		K_2	0.7071	0.5231		=	22.91
Repeatability & Reproducibility (GRR)						*Gage system may be acceptable*		
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$		**Parts**	K_3	% GRR/TT	=	100 (GRR/(TOL/6))
	=	{(0.025^2 + 0.004^2)}^1/2		2	0.7071		=	100(0.025/0.250)
	=	0.025		3	0.5231		=	10.05
Part Variation (PV)				4	0.4467	*Gage system may be acceptable*		
PV	=	R_P x K_3		5	0.4030	% PV	=	100 (PV/(TOL/6))
	=	0.265 x 0.403		6	0.3742		=	100(0.107/0.250)
	=	0.107		7	0.3534		=	42.72
Total Variation (TV)				8	0.3375	**Number of Distinct Categories (ndc)**		
TV	=	$\{(GRR^2 + PV^2)\}^{1/2}$		9	0.3249	**ndc**	=	1.41(PV/GRR)
	=	{(0.025^2 + 0.107^2)}^1/2		10	0.3146		=	1.41(0.107/0.025)
	=	0.110					=	5.99

Figure 8: Gage Repeatability and Reproducibility Worksheet

Process Capability

General Motors wanted Vermont Composites to develop a process capable of yielding a PPK of 1.333 or greater. This variation is equivalent to 8 Sigma or 8 times the standard deviation of the measurements. We had to get tolerance relief in 8 of the 28 points, two points the total tolerance was increased 0.1 mm to 1.6 mm, one point was increased 0.2 mm to 1.7 mm, three points were increased 0.3 mm to 1.8 mm and finally two points were increased 0.7 mm to 2.2 mm. In all cases the PPK's are now averaging greater than 1.0 (6 Sigma).

The two points, which had to have the most tolerance given, were flush points, one is over the unsupported headlamp and the other is in the very thin (0.8 mm) rocker area below the gill. General Motors wanted to keep the area below the gill very thin in order to chase build variation as low on the car as possible. Note the up/down datum's react against each other in this area below the rocker. The up/down datum surface on the bottom rear edge of the rocker clamps upward while the rest of the up/down datum's react downwards. Refer to figure #9 for an example of a typical Process Capability worksheet.

Conclusions

Vermont Composites, Inc. is fairly confident that we have proven the ability of carbon fiber reinforced epoxy composites to produce dimensionally acceptable exterior body components when subjected to the industries normal tolerances with better than 6 sigma Statistical Process Control requirements of the Production Part Approval Process (PPAP). Surface tolerances of +/- 0.75 mm have been demonstrated as possible to hold given very careful attention to part design, machining fixture design, gage design and process controls in the component manufacturing process.

Figure 9: Example Spreadsheet of Process Capability Results:

Date	Tool #	SERIAL #	1 FNCFSPK010	2 FNCOHPK031	3 FNCUSPK034	4 FNCFHPK032	5 FNCUSPK035	6 FNCOSPK036
		USL	0.5	0.6	1.4	0.75	1.4	0.75
		LSL	-1	-0.9	-0.8	-0.75	-0.1	-0.75
			GAP	GAP	FLUSH	GAP	FLUSH	FLUSH
05/19/05	3	473	-0.55	-0.46	-0.14	-0.39	0.47	-0.44
05/19/05	4	474	-0.6	-0.17	0.6	-0.2	0.74	-0.3
05/19/05	3	479	-0.69	-0.54	-0.26	-0.29	0.46	-0.02
05/19/05	2	481	-0.25	-0.05	0.56	0.01	1.05	0.24
05/19/05	4	482	-0.61	-0.13	1.2	-0.33	1.15	0.23
05/19/05	2	477	-0.27	-0.16	0.38	-0.08	0.94	-0.06
05/19/05	3	483	-0.51	-0.44	0.17	-0.14	0.75	0.14
05/19/05	1	484	-0.44	-0.53	0.11	-0.32	0.57	0.17
5/20/2005	2	485	-0.26	-0.32	0.39	-0.25	0.58	0.14
5/20/2005	4	486	-0.74	-0.49	0.39	-0.4	0.85	0
5/20/2005	1	488	-0.51	-0.37	-0.16	-0.21	0.55	0.06
5/20/2005	4	491	-0.65	-0.23	0.78	-0.3	1.06	0.15
05/23/05	2	489	-0.31	-0.23	0.68	-0.22	0.84	0.18
05/23/05	2	498	-0.35	-0.25	0.43	-0.1	0.84	0.14
05/23/05	3	490	-0.55	-0.52	0.49	-0.46	0.78	0.08
05/23/05	4	495	-0.62	-0.38	0.43	-0.22	0.7	0.01
05/23/05	1	496	-0.55	-0.59	-0.19	-0.26	0.45	-0.11
05/23/05	3	497	-0.60	-0.51	0.09	-0.15	0.69	0.07
05/23/05	3	494	-0.52	-0.54	0.15	-0.45	0.6	0.08
05/23/05	1	493	-0.36	-0.45	0.15	-0.18	0.78	0.31
05/23/05	2	503	-0.34	-0.21	0.2	0.00	0.95	0.09
05/23/05	4	504	-0.6	-0.23	0.31	-0.19	0.74	0.03
05/24/05	1	507	-0.32	-0.35	0.38	-0.21	0.63	0.21
05/24/05	2	509	-0.24	-0.12	0.29	0.00	0.72	0.22
05/24/05	2	505	-0.29	-0.15	0.62	-0.06	0.87	0.44
05/24/05	3	508	-0.49	-0.38	0.46	-0.38	0.57	0.03
05/24/05	3	506	-0.56	-0.46	0.51	-0.40	0.87	0.01
05/25/05	1	510	-0.50	-0.63	0.17	-0.33	0.67	0.40
05/25/05	2	512	-0.38	-0.25	0.07	-0.10	0.70	0.14
05/25/05	3	514	-0.6	-0.4	0.17	-0.17	0.74	0.02
05/25/05	2	516	-0.29	-0.14	0.31	0.05	0.74	0.21
05/25/05	1	513	-0.33	-0.38	0.79	-0.45	0.65	0.09
05/25/05	1	515	-0.45	-0.5	0.32	-0.22	0.9	0.52
05/26/05	4	517	-0.66	-0.23	1.01	-0.48	0.64	-0.07
05/26/05	2	518	-0.25	-0.09	0.48	-0.15	0.73	0.09
05/26/05	3	519	-0.55	-0.41	0.31	-0.28	0.77	-0.07
05/26/05	1	522	-0.49	-0.57	0.18	-0.24	0.95	0.4
05/26/05	3	523	-0.57	-0.48	0.31	-0.35	0.86	0.18

Average	-0.47	-0.35	0.35	-0.23	0.75	0.11
Std. Dev.	0.144	0.161	0.309	0.140	0.166	0.184
Min	-0.74	-0.63	-0.26	-0.48	0.45	-0.44
Max	-0.24	-0.05	1.20	0.05	1.15	0.52
Range	0.50	0.58	1.46	0.53	0.70	0.96
Pp	1.733	1.549	1.188	1.780	1.509	1.357
PpK	1.225	1.134	1.139	1.224	1.305	1.166