Mechanical Properties – Structure Correlation
For Commercial Specification of Cast Particulate Metal Matrix Composites

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SUMMARY

In this research, the effects of casting foundry, testing laboratory, surface conditions, and casting processes on the mechanical properties of A359-SiC composites were identified. To observe the effects, A359-SiC composites with 20 and 305 SiC particles were cast at three different foundries and tested at three different laboratories. The composites were cast in sand and permanent molds and tested as-cast and machined conditions. To identify the effect of the volume fraction and distribution of particles on the properties of the composites, particle distribution was determined using Clemex Image analysis systems, and particle volume fraction was determined using wet chemical analysis and Clemex Image analysis systems. The microstructure and fractured surfaces of the samples were analyzed using SEM, and EDX analysis was done to analyze chemical reaction between the particles and the matrix.

The results of the tensile strengths exhibited that the tensile strengths depend on the density and porosity of the composites; in general the higher tensile strength is associated with lower porosity and higher density. In some cases, composites with lower density were higher than these with higher density. In the Al-20% SiC samples, the composites with more inclusions exhibited a lower tensile strength than the ones with fewer inclusions. This suggests that macroscopic casting defects such as micro-porosity, shrinkage porosity and inclusions appear to strongly influence the tensile strength more than the microstructure and particle distribution.

The fatigue properties of A359/20 vol.% SiC composites were investigated under strain controlled conditions. Hysteresis loops obtained from strain controlled cyclic loading of 20% SiCp reinforced material did not exhibit any measurable softening or hardening. The fatigue life of Al-20% SiC heat treated alloy at a given total strain showed wide variation in fatigue life, which appeared to be related to factors such as inclusions, porosity, and particle distribution. The inclusions and porosity on the fracture surfaces seem to have a more significant influence on the fatigue life of cast Al-20% SiC as compared to other variables, including SiC particle volume percentage and its distribution. Striations were generally not visible on the fracture surface of the composites. In many specimens, SiC particle fracture was also observed. Fracture was more severe around pores and inclusions than in the matrix away from them. Inclusions and porosity seem to have a much stronger influence on fatigue behavior than the particle distribution. The analysis suggests that the enhancement of fatigue behavior of cast MMCs requires a decrease in the size of defects, porosity, and inclusions.

The particle volume fraction determined using wet chemical analysis gives values of SiC vol.% which are closer to the nominal SiC % than the values of SiC% obtained by ultrasonic and Clemex Image Analysis system. In view of ALCAN'S recommendation one must use wet chemical analysis for determining the volume percent SiC.

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Appendix II: Paper entitled “Fatigue Behavior of Permanent Mold Cast A356- 20% SiC Composite” accepted for Publication in 2003 Transactions.	
Appendix III: Paper entitled “Scatter in Tensile Properties of Cast A359-SiC aluminum alloys” accepted for Publication in 2003 Transactions.	
Appendix IV: Paper entitled “Tensile and Fatigue Properties of Permanent mold Cast A359-SiCp Aluminum Alloys”, published in TMS Annual Meeting in Indianapolis, 2001.	
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1. INTRODUCTION

SiC particle reinforced metal matrix composites (SiC_p/Al MMCs) are becoming popular because of their excellent combination of properties such as high strength to weight ratio, high specific stiffness, high thermal and electrical conductivity, low to moderate thermal expansion and improved wear resistance. Because of these properties MMCs have found applications in Aerospace [1,2], Automotive [3,4,5], Recreation [6] and Thermal Management industries. Recently SiC particulate reinforced cast Aluminum MMCs have been developed for many automobile and aerospace applications. In most cases Al-SiC composites show better properties than grey cast iron (GCI). Current applications of Al-SiC_p in automobile and aerospace industries include brake rotors, brake drums, cylinder liners, differential housings, Hubble Telescope Antenna and microwave thermal package used in LEO satellites [7,14].

Solidification processing has been the most common technique to produce Al-SiC_p MMCs due to its low cost of fabrication. Compared with the solid state processing such as powder metallurgy [6], solidification processing involves stir casting technique [15] which is economical and very effective in producing discontinuous ceramic reinforced metal matrix composites, including Al-SiC_p. The added advantage of this technique is that it is simple to use and offers the possibility of producing a wide range of casting sizes and shapes.

In order to increase the use of the MMCs, it is vital that the design engineers are provided with the “Handbook” type material data that is reliable including the variability expected in their properties. The handbook type data is necessary because for any engineering application, the functionality and reliability of any composite material must be checked at first before evaluating its manufacturability and recyclability. The attempt is made in this report to provide this type of information for SiC_p reinforced Al359 MMC.

Mechanical properties of SiC particle reinforced aluminum matrix composites are influenced by the structure of composites. The main factors that decrease mechanical properties of the composites are casting defects such as shrinkage, porosity, extraneous phases including oxides, and clustering of silicon carbide particles. Insufficient mixing, slow solidification rates, particle sedimentation and particle pushing during solidification can cause this problem. As described below, we have tried to provide answers to most, if not all the factors that influence the properties of SiC_p reinforced Al359 MMC and also provide handbook type data for the material including the expected variability in its properties.

Based upon the aforementioned requirements, the project was undertaken to evaluate mechanical properties and structural characterization procedures of commercially available aluminum-silicon carbide composites. Therefore, the objectives were to analyze the influence of (a) percentage silicon carbide, (b) mold type, (c) material source, (d) casting foundry, (e) machining of tensile bar, and (f) testing laboratory on mechanical properties of Al-20% SiC and Al-30% SiC composites. It was felt that this evaluation will help in identifying the uniform and standard procedures for testing cast metal matrix

composites and also the casting procedure which would reduce variability in properties. Three different foundries and three independent test laboratories were used in the study in order to determine the reproducibility in properties in a given composite. Selected cast tensile bars from one foundry were also machined to smaller size fatigue bars and fatigue tested under strain-controlled mode to study the cyclic behavior of the Al-SiCp composite and to determine their fatigue properties. The coefficients of fatigue life equation together with the equation for total strain as a function of fatigue life were determined.

This research was conducted by the University of Wisconsin-Milwaukee and industry participants including all major auto makers – GM, Ford and Chrysler and several major US foundries including Eck Industries and Thompson Aluminum.

Based upon the objectives outlined above the “Scope of Work” was broken up as follows.

SCOPE OF WORK

- DEVELOP RANDOMIZATION PROTOCOL, TESTING AND CHARACTERIZATION PROTOCOL
- CASTING AND QUALIFICATION OF TEST BARS
- DISTRIBUTION OF TEST BARS TO VARIOUS TESTING SITES
- EVALUATION OF TENSILE AND FATIGUE PROPERTIES
- CHARACTERIZATION OF MICROSTRUCTURE
- COMPILATION OF DATA BASE
- FINAL REPORT

This final report, the annual reports for individual years and the published papers (included in the Appendix to this report) represent the outcome from the project work. The research papers published or accepted for publication and attached in Appendix represent versions incorporating reviewers’ comments; these research papers incorporate the most significant findings of this project work. The bulk of additional data in this report is incorporated in this annual report at the direction of AFS Committee 2F which wanted all data which is not in the papers to be incorporated in the report.

2. EXPERIMENTAL PROCEDURE

2.1 Tensile Test Bars

699 T6 heat-treated tensile test bars were received from Eck industries (Table 2-1). They were randomized and then sent to GM, Ford and Chrysler. Numbers in the table indicate serial numbers of bars. Code numbers are explained in Table 2-2.

Table 2-1 List of tensile test bars received from Eck Industries

		Received Number									
		7/29/98	8/5/98	8/12/98	9/14/98	2/9/99	3/19/99	5/4/99	6/2/99	8/26/99	Total #
Code No.	D1S	1	3	7	14	13	4	3	7	7	59
	E1S	9	5	4	5	10	5	3	0	1	42
	D1P	5	6	6	14	12	5	3	4	8	63
	E1P	0	0	0	30	6	0	1	17	0	54
	C2S	1	3	4	17	11	3	6	6	9	60
	C2P	27	3	6	8	7	1	2	3	3	60
	D2S	7	6	3	7	7	7	7	7	10	61
	D2P	17	8	7	2	12	2	4	6	3	61
	C3S	16	4	2	14	8	3	6	3	5	61
	C3P	11	7	9	13	8	3	2	1	6	60
	E4S	10	10	3	3	9	2	2	8	12	59
	E4P	13	1	3	6	14	5	6	3	8	59
Sub Total Number		117	56	54	133	117	40	45	65	72	699
Total Number		699									

Table 2-2 Code number of tensile test bars:

ALLOY	MATERIAL CODE	PROCESS	PROCESS CODE	FOUNDRY	FOUNDRY CODE
Lanxide 4040-30P	1	Sand mold	S	Duralcan	C
Duralcan F3S.20S	2	Permanent mold	P	Eck Industries	D
Duralcan F3S.30S	3			Lanxide	E
Lanxide 1060-30P	4			Thompson	F

ID CODE FOR SAMPLES: MATERIAL-PROCESS-FOUNDRY-SERIAL NO.

EXAMPLE: E1S = LANXIDE ALLOY, SAND MOLD, LANXIDE FOUNDRY

2.2 SEM EDX Analysis of the Fracture Surface of Broken Tensile Test Bars

The fracture surfaces of selected tensile test bars after testing were analyzed using SEM-EDX. Table 2-3 is a listing of bars with high, medium, and low tensile strength that were analyzed using this technique. The results of the analysis are discussed in Chapter 3.8 with the aid of spectrums obtained from SEM-EDX

Table 2-3. Tensile Test Bars Examined by SEM-EDX after testing

CODE NO.	D2P	C2P	E1P	C3S	C3P
HIGHEST T. S.	23	16	11	50	
MEDIUM T. S.	2	19	55	6	39
LOWEST T. S.	52	8	48	27	36

2.3 Ultrasonic velocity measurement to estimate mechanical properties and silicon carbide percentage:

The tensile test bars from GM were selected for measurement of ultrasonic velocities. The velocity measurements can be used to estimate the modulus of the bars, and to estimate the volume percentage of SiC particles. In each set, three tensile test bars, which had the highest, medium and lowest tensile strength, were selected for ultrasonic velocity measurements. The estimates of modulus and volume percentage silicon carbide using ultrasonic velocity measurement are shown in Table 2-4.

Table 2-4: Use of Ultrasonic Velocity Measurements on Al-SiC broken Tensile Bars for Determination of Mechanical Properties

Sample ID	Long. Velocity m/sec	Shear Velocity m/sec	Poisson Ratio	Elastic Modulus GPa	Shear Modulus GPa	Nominal SiC Vol. %	Calculated SiC Vol. %
C2P8	7223	3827	0.305	105.0	40.2	20	18.86
C2P19	7247	3776	0.314	102.9	39.2	20	19.45
C2P37	7046	3816	0.293	103.7	40.1	20	14.57
C3P39	7473	4123	0.281	124.2	48.5	30	24.95
C2P43	7065	3799	0.297	101.9	39.3	20	15.04
D2P2	7191	3831	0.302	105.7	40.6	20	18.08
D2P5	7203	3835	0.302	104.2	40.0	20	18.38
D2P18	7328	3859	0.308	104.2	39.8	20	21.43
D2P23	7195	3823	0.303	104.4	40.0	20	18.19
D2P35	7110	3939	0.279	108.1	42.3	20	16.13
D2P52	7265	3808	0.311	365.6	139.5	20	19.89
E1P2	7574	4156	0.285	124.3	48.4	30	27.41
C3S6	7648	4169	0.289	125.1	48.5	30	29.19
C3S20	7676	4249	0.279	129.3	50.6	30	29.88
C3S27	7161	4020	0.270	115.0	45.3	30	17.37
C3S31	7745	4264	0.283	131.0	51.1	30	31.56
C3S50	7387	4078	0.281	119.8	46.8	30	22.86
C3P4	7606	4176	0.284	N/A	N/A	30	28.19
C3P5	7601	4126	0.291	123.6	47.9	30	28.07
C3P26	7485	4103	0.285	121.2	47.1	30	25.23

C3P36	7579	4150	0.286	123.6	48.1	30	27.51
C3P43	7239	4148	0.256	121.0	48.2	30	19.27
C3P56	7602	4121	0.292	122.0	47.2	30	28.08
E1P11	7498	4196	0.272	122.8	48.3	30	25.55
E1P48	7765	4190	0.295	127.3	49.2	30	32.04
E1P55	7538	4209	0.274	126.1	49.5	30	26.53
E1P1	7636	4199	0.283	127.1	49.5	30	28.90
E1P32	7651	4208	0.283	124.5	49.5	30	29.28

2.4 Measurement of SiC content by chemical dissolution method:

In order to determine the SiC content of tensile test bars more accurately, wet chemical dissolution method was used at Oshkosh Truck. The earlier test practice adopted at Oshkosh did not conform to the standard devised by ALCAN, the producer of Al-SiC ingots. The volume % of SiC obtained from this method was at considerable variance with the nominal volume % SiC specified by the producer. Hence the analysis of volume percent silicon carbide using matrix dissolution procedure was redone on selected samples using the ALCAN procedure. Newly generated data on some samples indicated that % SiC determined by the ALCAN wet chemical analysis procedure is closer to the nominal value. The procedure was applied to repeat the analysis on remaining samples. A full set of data obtained from Oshkosh on wet chemical analysis is attached as an Appendix. There is a growing consensus that wet chemical analysis gives the most reliable estimates of volume fraction SiC; however, the wet chemical method is destructive and does not given an idea of the particle distribution or porosity in the microstructure which influences properties.

2.5 Study of Microstructure of Tensile Tested Samples:

The microstructure of selected tensile tested samples was analyzed for % SiC and Si, aspect ratios of SiC and Si, and % porosity using the Clemex Image Analysis system. The values generated were correlated with tensile strength measurements.

3. Tensile Properties of Cast Bars of Al-20% SiC and Al-30% SiC Composites

3.1 Analysis of Data Generated in 1999: Basic statistical analysis was performed on the data received from General Motors (GM), Ford and Daimler Chrysler. The data and the statistics are tabulated in tables below.

Table 3.1.1: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at Duralcan and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C2P9	50.610	14560	345.67	99.44
C2P10	50.106	14540	342.22	99.31
C2P26	49.107	*****	335.40	*****
C2P32	46.660	*****	318.69	*****
C2P37	49.730	14110	339.66	96.37
C2P43	53.083	14560	362.56	99.44
Average:	49.883	14440	340.70	98.63
Standard Deviation:	2.090	220	14.27	1.5
Maximum	53.083	14560	362.56	99.44
Minimum	46.660	14110	318.69	96.37

Table 3.1.2: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at ECK Industries, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
D2P5	49.528	14300	338.28	97.67
D2P12	47.503	14780	324.45	100.95
D2P15	47.064	14520	321.45	99.17
D2P18	48.676	14490	332.48	98.97
D2P30	49.482	14660	337.96	100.13
D2P35	46.263	14830	315.98	101.29
Average:	48.086	14600	328.43	99.72
Standard Deviation:	1.348	200	9.21	1.4
Maximum	49.528	14830	338.28	101.29
Minimum	46.263	14300	315.98	97.67

Table 3.1.3: Mechanical properties of Sand Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3S17	45.641	*****	311.73	*****
C3S20	42.710	16490	291.71	112.63

C3S31	46.843	*****	319.94	*****
C3S38	43.024	*****	293.85	*****
C3S43	44.387	16470	303.16	112.49
C3S45	45.743	16630	312.42	113.58
Average:	44.725	16530	305.47	112.90
Standard Deviation:	1.639	90	11.19	0.6
Maximum	46.843	16630	319.94	113.58
Minimum	42.710	16470	291.71	112.49

Table 3.1.4: Mechanical properties of Permanent Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3P2	42.49	16660	290.21	113.79
C3P4	41.491	16420	283.38	112.15
C3P5	45.831	16760	313.03	114.47
C3P26	47.043	*****	321.30	*****
C3P37	46.236	17210	315.79	117.54
C3P43	46.116	16750	314.97	114.40
Average:	44.868	16760	306.45	114.47
Standard Deviation:	2.287	290	15.62	2.0
Maximum	47.043	17210	321.30	117.54
Minimum	41.491	16420	283.38	112.15

Table 3.1.5: Mechanical properties of Permanent Mold, Machined, 30% SiC, Lanxide 4040-30P Alloy, Cast at Lanxide, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
E1P1	47.27	17060	322.88	116.52
E1P2	51.88	16810	354.33	114.81
E1P9	48.20	16820	329.20	114.88
E1P23	48.27	17180	329.66	117.34
E1P26	51.82	17260	353.90	117.89
E1P32	52.73	17070	360.12	116.59
Average:	50.03	17030	341.70	116.30
Standard Deviation:	2.36	190	16.12	1.3
Maximum:	52.73	17260	360.12	117.89
Minimum	47.27	16810	322.88	114.81

Table 3.1.6: Mechanical properties of Permanent Mold, As Cast, 20% SiC, Duralcan F3S.20S Alloy, Cast at Duralcan, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C2P6	47.509	14540	324.49	99.31

C2P8	47.336	13540	323.30	92.48
C2P16	50.869	13640	347.44	93.16
C2P19	49.186	14220	335.90	97.12
C2P25	48.641	14180	332.22	96.85
C2P33	50.810	14230	347.03	97.19
Average:	49.059	14060	335.07	96.03
Standard Deviation:	1.543	390	10.54	2.7
Maximum	50.869	14540	347.44	99.31
Minimum	47.336	13540	323.30	92.48

Table 3.1.7: Mechanical properties of Sand Mold, As Cast, 20% SiC, Duralcan F3S.20S Alloy, Cast at ECK Industries, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
D2P2	48.083	14440	328.41	98.63
D2P14	49.553	13650	338.45	93.23
D2P23	49.556	13630	338.47	93.09
D2P27	49.180	13920	335.90	95.07
D2P52	45.328	13940	309.59	95.21
Average:	48.340	13920	330.16	95.07
Standard Deviation:	1.788	330	12.21	2.3
Maximum	49556	14440	338.47	98.63
Minimum	45328	13630	309.59	93.09

Table 3.1.8: Mechanical properties of Sand Mold, As Cast, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3S4	43.998	16610	300.51	113.45
C3S6	44.349	16610	302.90	113.45
C3S22	46.284	16400	316.72	112.01
C3S27	41.051	16280	280.13	111.19
C3S48	42.030	*****	287.06	*****
C3S50	46.630	*****	318.48	*****
Average:	44.051	16480	300.87	112.56
Standard Deviation:	2.237	160	15.28	1.1
Maximum	46630	16610	318.48	113.45
Minimum	41.051	16280	280.13	111.19

Table 3.1.9: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3P28	47.238	16410	322.64	112.08

C3P32	39.970	16740	273.00	114.33
C3P36	35.687	16930	243.74	115.63
C3P39	41.448	16270	283.09	111.12
C3P42	48.336	16440	330.13	112.29
C3P56	49.881	16850	340.69	115.09
Average:	43.760	16610	298.88	113.45
Standard Deviation:	5.575	270	38.08	1.8
Maximum	49.881	16930	340.69	115.63
Minimum	35.687	16270	243.74	111.12

Table 3.1.10: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Lanxide 4040-30P Alloy, Cast at Lanxide, and tested at GM - Data received 3/18/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
E1P11	51.465	17140	351.51	117.07
E1P30	45.247	16980	309.04	115.97
E1P48	45.098	17040	308.02	116.38
E1P55	46.491	16520	317.53	112.83
Average:	47.075	16920	321.40	115.56
Standard Deviation:	2.992	280	20.44	1.90
Maximum	51.465	17140	351.51	117.07
Minimum	45.098	16520	309.04	112.83

Table 3.1.11: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5 /1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C2P1	49.509	16738	338.15	114.32
C2P5	52.158	16459	356.24	112.41
C2P28	51.786	16307	353.70	111.38
C2P38	53.500	13817	365.41	94.37
C2P52	52.146	14768	356.16	100.87
C2P54	50.627	16184	345.78	110.54
Average:	51.621	15712	352.57	107.31
Standard Deviation:	1.383	1155	9.45	7.9
Maximum	53.500	14560	365.41	114.32
Minimum	49.509	14110	338.15	94.37

Table 3.1.12: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at ECK, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
D2P4	48.400	15591	330.57	106.49
D2P13	48.534	16341	331.49	111.61

D2P16	50.366	18895	344.00	129.05
D2P19	50.340	15772	343.82	107.72
D2P40	51.305	16368	350.41	111.79
D2P55	48.771	15470	333.11	105.66
Average:	49.620	16406	338.90	112.05
Standard Deviation:	1.208	1276	8.25	8.72
Maximum	51.305	18895	350.41	101.29
Minimum	48.400	15470	330.57	97.67

Table 3.1.13: Mechanical properties of Sand Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3S10	46.361	16692	316.65	114.01
C3S14	40.426	15590	276.11	106.48
C3S26	45.316	17721	309.51	121.03
C3S32	48.163	19821	328.95	135.38
C3S40	47.532	15309	324.64	104.56
C3S44	44.981	19059	307.22	130.21
Average:	45.463	17365	310.51	118.60
Standard Deviation:	2.757	1836	18.83	12.54
Maximum:	48.163	19821	328.95	135.38
Minimum	40.426	15309	276.11	104.56

Table 3.1.14: Mechanical properties of Permanent Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3P6	45.858	16300	313.21	111.33
C3P13	49.164	18026	335.79	123.12
C3P35	46.413	18378	317.00	125.52
C3P51	42.972	17786	293.50	121.48
C3P58	45.611	19881	311.52	135.79
C3P59	51.453	25652	351.42	175.20
Average:	46.913	19337	320.42	132.07
Standard Deviation:	2.809	3300	19.19	22.54
Maximum	51.453	25652	351.42	175.20
Minimum	42.972	16300	293.50	111.33

Table 3.1.15: Mechanical properties of Permanent Mold, Machined, 30% SiC, Lanxide 4040-30P Alloy, Cast at Lanxide, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
E1P3	48.972	28432	334.48	194.19

E1P5	52.132	22118	356.06	151.07
E1P12	52.377	21560	357.03	147.25
E1P15	46.981	21204	320.88	144.82
E1P17	48.838	22196	333.56	151.60
E1P52	45.232	18667	308.93	127.50
Average:	49.089	22363	335.28	152.74
Standard Deviation:	2.809	3242	19.19	22.14
Maximum Tensile:	52.377	28432	357.03	194.19
Minimum Tensile:	45.232	18667	320.88	127.50

Table 3.1.16: Mechanical properties of Permanent Mold, As Cast, 20% SiC, Duralcan F3S.20S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5 /1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C2P31	52.721	14975	360.08	102.28
C2P41	54.453	18554	371.91	126.72
C2P46	51.001	14956	348.34	102.15
C2P48	53.428	23368	364.91	159.60
C2P53	55.389	18420	378.31	125.81
C2P59	54.436	18083	371.80	123.51
Average:	53.572	18059	365.90	123.34
Standard Deviation:	1.56	3089	10.65	21.10
Maximum	55389	23368	378.31	159.60
Minimum	51001	14975	348.34	102.15

Table 3.1.17: Mechanical properties of Permanent Mold, As Cast, 20% SiC, Duralcan F3S.20S Alloy, Cast at ECK, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
D2P9	50.566	16310	345.37	111.40
D2P10	47.904	13958	327.18	95.33
D2P20	53.164	14383	363.11	98.24
D2P26	50.039	14191	341.77	96.92
D2P39	47.958	14277	327.55	97.51
Average:	49.927	14624	341.00	99.88
Standard Deviation:	2.172	955.6	14.83	6.53
Maximum	53.164	16310	363.11	111.40
Minimum	47.904	13958	327.18	95.33

Table 3.1.18: Mechanical properties of Sand Mold, As Cast, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3S2	43.814	19420	299.25	132.64

C3S12	39.763	12979	271.58	88.65
C3S15	40.45	31225	276.27	213.27
C3S37	47.407	21555	323.79	147.22
C3S42	47.232	22038	292.22	150.52
C3S52	49.727	24442	335.19	166.94
Average:	43.883	21943	299.72	149.87
Standard Deviation:	3.725	5988	25.44	40.90
Maximum	49.727	31225	335.19	213.27
Minimum	39.763	12979	271.58	88.65

Table 3.1.19: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3P10	49.533	28739	338.31	196.29
C3P14	54.398	13921	371.54	95.08
C3P20	50.073	19089	342.00	130.38
C3P25	47.501	7166	324.43	48.94
C3P29	47.233	9913	322.59	67.71
C3P34	49.727	14233	339.64	97.21
Average:	49745	15510	339.76	105.93
Standard Deviation:	2.57	7654	17.55	52.28
Maximum	54.398	28739	371.54	196.29
Minimum	47.233	7166	322.59	48.94

Table 3.1.20: Mechanical properties of Permanent Mold, AS Cast, 30% SiC, Lanxide 4040-30P Alloy, Cast at Lanxide, and tested at Ford - Data received 3/5/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
E1P7	49.761	12527	339.87	85.56
E1P14	55.425	61021	378.55	416.77
E1P42	52.111	19517	355.92	133.30
E1P50	49.782	19792	340.01	135.18
Average:	51.770	28214	353.59	192.70
Standard Deviation:	2.675	*****	18.27	*****
Maximum	55.424	61021	378.55	416.77
Minimum	49.761	12527	339.87	85.66

Table 3.1.21: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at Duralcan, and tested at Daimler Chrysler - Data received 6/29 /1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C2P11	45.463	17214	310.51	117.57

C2P21	50.952	23094	348.00	157.73
C2P22	47.67	18655	325.59	127.41
C2P40	52.653	13077	359.62	89.32
C2P42	48.508	15003	331.31	102.47
C2P57	51.791	15210	353.73	103.88
Average:	49.507	17072	338.13	116.6
Standard Deviation:	2.754	3535	18.81	24.14
Maximum	52.653	23094	353.73	157.73
Minimum	45.463	13077	310.51	89.32

Table 3.1.22: Mechanical properties of Permanent Mold, Machined, 20% SiC, Duralcan F3S.20S Alloy, Cast at ECK, and tested at Daimler Chrysler - Data received 6/29/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
D2P1	51.577	15322	352.27	104.65
D2P3	51.783	13546	353.68	92.52
D2P11	50.608	13824	345.64	94.42
D2P21	42.548	12536	290.60	85.62
D2P25	46.461	16492	317.53	112.64
Average:	48.595	14344	331.90	97.97
Standard Deviation:	4.006	1561	27.36	10.66
Maximum	51.783	16492	353.68	112.64
Minimum	42.548	12536	290.60	85.62

Table 3.1.23: Mechanical properties of Sand Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Daimler Chrysler - Data received 6/29/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3S7	43.562	21409	297.53	146.22
C3S19	41.633	25894	284.35	176.86
C3S28	46.754	17527	319.33	119.71
C3S47	46.935	23314	320.57	159.23
C3S51	40.861	13886	279.08	94.84
C3S58	43.641	16256	298.07	111.03
Average:	43.898	19714	299.82	134.65
Standard Deviation:	2.526	4577	17.25	31.26
Maximum	46.935	25894	320.57	176.86
Minimum	40.861	13886	279.08	94.84

Table 3.1.24: Mechanical properties of Permanent Mold, Machined, 30% SiC, Duralcan F3S.30S Alloy, Cast at Duralcan, and tested at Daimler Chrysler - Data received 6/29/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
C3P13	41.726	16477	284.99	112.54
C3P7	46.065	23255	314.62	158.83
C3P15	47.080	17704	321.56	120.92
C3P50	46.812	23052	319.73	157.45
C3P57				
C3P60				
Average:	45.421	20122	310.23	137.43
Standard Deviation:	2.5	3537	17.08	24.16
Maximum	47.080	23255	321.56	158.83
Minimum	41.726	16477	284.99	112.54

Table 3.1.25: Mechanical properties of Permanent Mold, Machined, 30% SiC, Lanxide 4040-30P Alloy, Cast at Lanxide, and tested at Daimler Chrysler - Data received 6/29/1999

SAMPLE ID	TENSILE STRENGTH (KSI)	MODULUS (KSI)	TENSILE STRENGTH (MPA)	MODULUS (GPA)
E1P6	51.743	16127	353.40	110.15
E1P8	46.351	15817	316.58	108.03
E1P10	51.100	17610	349.01	120.28
E1P18	48.293	17441	336.67	119.12
E1P21	48.771	17870	333.11	122.05
E1P33	55.053	16580	376.01	113.24
Average:	50.383	16907	344.12	115.47
Standard Deviation:	2.968	850	20.27	5.81
Maximum	55.053	17870	376.01	122.05
Minimum	46.351	15817	316.58	108.03

3.2 Additional Tensile Test Data Received from Daimler-Chrysler in 2001:

Tensile test data on remaining samples were received from Daimler-Chrysler in 2001. The basic statistical analysis was also performed on this data. The raw data and statistics are tabulated in following tables. The comparison of this data with the data received in 1999 from GM, Ford, and Daimler Chrysler show that the tensile strength values are comparable. However, the elastic modulus values of the data reported by Daimler Chrysler in 2001 were much lower than the data reported in 1999 by GM, Ford and Daimler Chrysler. DC was contacted to determine the cause of low values. Apparently there is an error in modulus values measured at DC due to errors in measurement of percent elongation. This points to the need to standardize the method of testing composites.

Table 3.2.1 Mechanical properties of Sandt Mold, As Cast 20% SiC, Duralcan F3S.20S alloy, Cast at Duralcan, and tested at Daimler Chrysler - Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
C2S2	37.621	355.955	259.36	2.45
C2S13	47.157	457.976	325.11	3.16
C2S19	45.228	496.568	311.80	3.42
C2S21	46.333	546.889	319.42	3.77
C2S23	45.555	369.355	314.06	2.55
C2S28	45.700	385.516	315.06	2.66
C2S31	40.702	394.382	280.61	2.72
C2S39	45.168	422.383	311.39	2.91
C2S40	43.769	415.333	301.74	2.86
C2S42	44.247	456.135	305.04	3.14
C2S58	47.233	401.656	325.62	2.77
C2S60	46402.84	469.990	319.90	3.24
Average:	44.593	431.012	307.43	2.97
Standard Deviation:	2.816.	56.110	19.42	0.39
Maximum	47.233	546.889	259.36	3.77
Minimum	37.621	355.955	325.62	2.45

Table 3.2.2: Mechanical properties of Sand Mold, As Cast 20% SiC, Duralcan F3S.20S alloy, Cast at ECK Industries and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
D2S6	47.899	470.312	330.22	3.24
D2S22	46.218	358.959	318.62	2.47
D2S28	42.691	396.469	294.31	2.73
D2S30	45.232.	480.727	311.83	3.31
D2S32	49.567	369.567	341.72	2.55
D2S39	46.6189	510.250	321.39	3.52
D2S46	47.501	399.390	327.47	2.75
D2S47	46.804	530.267	322.67	3.66
D2S50	44.012	369.183	303.42	2.55
D2S58	45.432	493.817	313.21	3.40
D2S74	46.987	490.717	323.92	3.38
Average:	46.269	442.696	318.98	3.05
Standard Deviation:	1.888	64.138	13.02	0.44
Maximum	49.567	530.267	341.72	3.66
Minimum	42.691	358.959	294.31	2.47

Table 3.2.3: Mechanical properties of Permanent Mold, 20% SiC, Duralcan F3S.20S alloy, Cast at Duralcan, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
C2P2	51.040	478.652	351.87	3.30
C2P4	51.120	489.672	352.42	3.38
C2P12	47.415	442.626	326.88	3.05
C2P27	48.600	488.308	335.05	3.37
C2P29	51.123	520.693	352.44	3.59
C2P58	52.053	488.777	358.85	3.37
Average:	50.225	484.788	346.25	3.34
Standard Deviation:	1.797	25.126	12.39	0.17
Maximum	52.053	520.693	358.85	3.59
Minimum	47.415	442.626	326.88	3.05

Table 3.2.4: Mechanical properties of Permanent Mold, As Cast, 20% SiC, Duralcan F3S.20S alloy, Cast at ECK Industries, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (psi)	Modulus (psi)	Tensile Strength (Mpa)	Modulus (Gpa)
D2P6	49.038	457.014	338.07	3.15
D2P37	44.862	473.820	309.28	3.27
D2P42	49.287	481.150	339.78	3.32
D2P50	49.992	481.802	344.64	3.32
D2P51	50.178	491.249	345.93	3.39
Average:	48.671	477.007	335.54	3.29
Standard Deviation:	2.182	12.775	15.04	0.09
Maximum	50.178	491.259	345.93	3.39
Minimum	44.862	457.014	309.28	3.15

Table 3.2.5: Mechanical properties of Sand Mold, As Cast, 30% SiC, Duralcan F3S.30S alloy, Cast at Duralcan, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
C3S21	39.494	424.581	272.27	2.93
C3S30	45.493	412.188	313.63	2.84
C3S33	49.892	444.370	343.95	3.06
C3S41	45.533	428.827	316.11	2.96
C3S46	30.569	164.958	210.74	1.14
C3S62	45.525	416.874	313.85	2.87

Average:	42.804	381.966	295.09	2.63
Standard Deviation:	6.854	106.893	47.25	0.74
Maximum:	49.892	444.370	343.95	3.06
Minimum	30.569	164.958	210.74	1.14

Table 3.2.6: Mechanical properties of Sand Mold, As Cast, 30% SiC, Lanxide 4040-30P alloy, Cast at ECK Industries, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
D1S1	37.900	393.777	261.29	2.71
D1S12	40.110	387.949	276.52	2.67
D1S14	39.351	410.542	271.29	2.83
D1S15	29.766	198.632	205.21	1.37
D1S18	34.967	355.499	241.07	2.45
D1S24	45.971	525.841	316.93	3.63
D1S35	44.498	530.355	306.77	3.66
D1S39	40.138	387.568	276.71	2.67
D1S48	41.482	481.980	285.97	3.32
D1S49	38.794	405.075	267.45	2.79
D1S51	41.707	426.107	287.53	2.94
D1S56	44.158	479.619	304.43	3.31
Average:	39.903	415.245	275.10	2.86
Standard Deviation:	4.416	88.823	30.45	0.61
Maximum	45.971	530.355	316.93	3.66
Minimum	29.766	198.632	205.21	1.37

Table 3.2.7: Mechanical properties of Sand Mold, As Cast, 30% SiC, Lanxide 4040-30P alloy, Cast at Lanxide, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (psi)	Modulus (psi)	Tensile Strength (Mpa)	Modulus (Gpa)
E1S2	41.997	375.691	289.53	2.59
E1S5	41.308	360.983	284.78	2.49
E1S6	42.883	401.958	295.63	2.77
E1S10	40.719	335.757	280.72	2.31
E1S11	41.004	351.654	282.68	2.42
E1S14	41.558	389.391	286.50	2.68
E1S17	44.336	392.576	305.65	2.71
E1S19	38.793	350.968	267.44	2.42
E1S20	41.887	355.404	288.77	2.45
E1S28	43.115	355.626	297.23	2.45

E1S34	42.358	370.197	292.02	2.55
E1S36	42.722	381.670	294.52	2.63
E1S59	53.571	450.426	369.32	3.11
E1S49	47.620	368.939	328.29	2.54
Average:	43.134	374.374	297.36	2.58
Standard Deviation:	3.608	28.621	24.87	0.20
Maximum	53.571	450.426	369.32	3.11
Minimum	38.793	335.757	267.44	2.31

Table3.2.8: Mechanical properties of Sand Mold, As Cast, 30% SiC, Lanxide 1060-30P alloy, Cast at Lanxide, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
E4S6	34.107	251.125	235.13	1.73
E4S10	41.364	382.182	285.17	2.63
E4S15	40.038	366.991	276.02	2.53
E4S16	35.906	291.182	247.54	2.01
E4S18	40.524	370.307	279.37	2.55
E4S20	40.393	380.076	278.47	2.62
E4S25	39.535	386.853	272.55	2.67
E4S35	34.532	366.466	238.06	2.53
E4S36	35.733	318.962	246.34	2.20
E4S42	39.270	351.557	270.72	2.42
E4S50	42.858	384.760	295.47	2.65
E4S56	39.270	389.712	270.70	2.69
Average:	38.627	353.347	266.30	2.44
Standard Deviation:	2.840	43.821	19.58	0.30
Maximum	42.858	389.712	295.47	2.69
Minimum	34.107	251.125	235.13	1.73

Table 3.2.9: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Duralcan F3S.30Salloy, Cast at Duralcan, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
C3P3	49.089	458.285	338.42	3.16
C3P9	46.198	404.514	318.49	2.79
C3P12	48.924	521.673	337.29	3.60
C3P21	42.115	457.736	290.34	3.16
C3P24	47.434	473.645	327.01	3.27

C3P41	38.386	428.056	264.63	2.95
Average:	45.358	457.318	312.70	3.15
Standard Deviation:	4.261	40.134	29.38	0.28
Maximum	49.089	521.673	338.42	3.60
Minimum	38.386	404.514	264.63	2.79

Table 3.2.10: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Lanxide 4040-30P alloy, Cast at ECK Industries, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
D1P5	41,906	571,551	288.91	3.94
D1P14	41,535	584,138	286.35	4.03
D1P22	41,988	527,649	289.47	3.64
D1P25	43,433	429,348	299.43	2.96
D1P27	42,379	392,402	292.17	2.71
D1P33	44,028	580,049	303.53	4.00
D1P37	44,087	503,896	303.94	3.47
D1P41	41,477	454,933	285.95	3.14
D1P43	43,933	552,729	302.88	3.81
D1P50	45,422	478,503	313.14	3.30
D1P56	39,900	447,677	275.07	3.09
D1P58	40,662	450,301	280.33	3.10
Average:	42,563	497,764	293.43	3.43
Standard Deviation:	1,624	64,931	11.20	0.45
Maximum:	45,422	584,138	313.14	4.03
Minimum	39,900	392,402	275.07	2.71

Table 3.2.11: Mechanical properties of Permanent Mold, As Cast, 30% SiC, Lanxide 4040-30P alloy, Cast at ECK Industries, and tested at Daimler Chrysler-Data received in 2001

Sample ID	Tensile Strength (Ksi)	Modulus (Ksi)	Tensile Strength (Mpa)	Modulus (Gpa)
E4P5	51.330	417.189	353.87	2.88
E4P6	50.013	581.218	344.79	4.01
E4P8	49.907	577.015	344.06	3.98
E4P12	47.793	427.371	329.49	2.95
E4P14	45.172	539.957	311.42	3.72
E4P18	47.842	437.929	329.82	3.02
E4P19	49.702	539.230	342.65	3.72

E4P21	50.037	439.636	344.96	3.03
E4P29	46.963	593.898	323.77	4.09
E4P33	48.320	601.197	333.12	4.14
E4P43	45.853	414.454	316.11	2.86
E4P56	43.075	411.843	296.96	2.84
Average:	48.001	498.411	330.92	3.44
Standard Deviation:	2.411	79.435	16.62	0.55
Maximum	51.330	601.197	353.87	4.14
Minimum	43.075	411.843	296.96	2.84

3.3 Comparison of Tensile Strength: The test data received from GM, Ford Motor Co., and Daimler Chrysler in 1999 was analyzed using commercially available statistical software SYSTAN to facilitate the comparison. The analysis represented in Tables 3.3.1 and 3.3.23 can be used to compare tensile strength data as follows:

1. Laboratory vs. laboratory
2. Effect of %SiC
3. Foundry vs. Foundry
4. Casting Process: Permanent vs. Sand
5. Supplier vs. Supplier
6. Surface Finish-Machined vs. As Cast

3.3.1: Laboratory vs. Laboratory Comparison:

In tables 3.3.1 to 3.3.10 the tensile strength data obtained in 1999 from GM (Lab. X), Ford Co. (Lab. Y), and Daimler Chrysler (Lab. Z) are compared to assess the effect of individual lab testing practices.

It is seen from Table 3.3.1 that the mean values of the tensile strength of Al-20%SiC composites cast at foundry C, collected from the three laboratories, are comparable, but the mean values from Lab. Y are slightly higher than those obtained from Lab. X and Lab. Z. The standard deviation of the data from Lab. Z is the highest while that of Lab. Y is the lowest.

Table 3.3.1: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.20S Permanent Mold, Machined Specimens cast at Duralcan (Foundry C)

	TENSILE STRENGTH-F3S.20S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-P	362.56	318.69	340.70	14.27	312.73	368.67
Lab-Y, Foundry-C, SF-M, Mold-P	365.41	338.15	352.57	9.45	334.05	371.09
Lab-Z, Foundry-C, SF-M, Mold-P	359.62	310.51	338.13	18.81	301.26	375.00

The mean values of the tensile strength of Al-20%SiC composites cast at foundry D, obtained from the three laboratories, are comparable, as shown in Table 3.3.2. However, the standard deviation of the data from Lab. Z is three times higher than that from either Lab. X or Lab. Y.

Table 3.3.2: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.20S Permanent Mold, Machined Specimens cast at ECK Industries (Foundry D)

	TENSILE STRENGTH-F3S.20S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-D, SF-M, Mold-P	338.28	315.98	328.43	9.20	310.40	346.46
Lab-Y, Foundry-D, SF-M, Mold-P	350.41	330.57	338.90	8.25	322.73	355.07
Lab-Z, Foundry-D, SF-M, Mold-P	353.68	290.60	331.90	27.37	278.25	385.55

From Tables 3.3.3 and 3.3.4, it is seen that the mean values of Al-20% SiC composites cast at Foundry C and Foundry D are significantly different. However the standard deviations are almost the same, indicating that the variability of data is the same. The measured tensile strength values from the two laboratories are within ± 0.2 standard deviations.

Table 3.3.3: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.20S Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	TENSILE STRENGTH-F3S.20S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-P	347.44	323.30	335.07	10.54	314.41	355.73
Lab-Y, Foundry-C, SF-AC, Mold-P	378.31	348.34	365.89	10.66	345.00	386.78

Table 3.3.4: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.20S Permanent Mold, As Cast Specimens cast at ECK Industries (Foundry D)

	TENSILE STRENGTH-F3S.20S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-D, SF-AC, Mold-P	338.47	309.59	330.16	12.22	306.21	355.73
Lab-Y, Foundry-D, SF-AC, Mold-P	363.11	327.18	341.00	14.84	311.91	370.09

It is seen from Table 3.3.5 that the mean values of Al-30%SiC composites cast in permanent molds at Foundry C are comparable within the experimental error. However, the measured values from Lab. Y are higher than those from either Lab. X or Lab. Z. Also, the standard deviation of the data from Lab. Y is higher than that from the other two. In Table 3.3.6, it is shown that the mean values of Al-30%SiC composites cast in sand molds at Foundry C are comparable within the experimental error. The standard deviation of the data from Lab. Y and Lab. Z is higher than that from Lab. X.

Table 3.3.5: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.30S Permanent Mold, Machined Specimens cast at Duralcan (Foundry C)

	TENSILE STRENGTH-F3S.30S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-P	321.30	283.38	306.44	15.61	275.84	337.04
Lab-Y, Foundry-C, SF-M, Mold-P	351.42	293.49	320.40	20.32	280.57	360.23
Lab.- Z, Foundry-C, SF-M, Mold-P	321.56	284.99	310.22	17.07	276.76	343.68

Table 3.3.6: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.30S Sand Mold, Machined Specimens cast at Duralcan (Foundry C).

	TENSILE STRENGTH-F3S.30S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-S	319.94	291.71	305.46	11.19	283.53	327.39
Lab-Y, Foundry-C, SF-M, Mold-S	328.95	276.11	310.51	18.82	273.62	347.40
Lab.- Z, Foundry-C, SF-M, Mold-S	320.57	279.08	299.82	17.25	266.01	333.63

Table 3.3.7 shows the results of the tensile strength of as-cast Al-30%SiC composites cast in permanent molds at Foundry C. It is seen that the measured tensile strength values from the two laboratories are significantly different. The standard deviation of the data from Lab. X is two times higher than that from Lab. Y. The mean and lower 95% value of Lab. X data falls outside the lower 95% value of Lab. Y. This observation indicates significant difference either in the lab practice or in microstructure of specimens tested by the two laboratories or both.

Table 3.3.7: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.30S Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	TENSILE STRENGTH-F3S.30S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-P	340.68	243.74	298.88	38.07	224.26	373.50
Lab-Y, Foundry-C, SF-AC, Mold-P	371.53	322.59	339.74	17.58	305.28	374.20

The mean tensile strength values of as-cast Al-30%SiC composites cast in sand molds at Foundry C, shown in Table 3.3.8, are comparable. However, the standard deviation of the data from Lab. Y is higher than that from Lab. X, indicating large variation in the measured data from Lab. Y. The measured tensile strength values from both laboratories are within ± 2 standard deviations. In Table 3.3.9, it is seen that the mean values and standard deviations of the data from three laboratories are comparable within the experimental error. The measured values are also not significantly different.

Table 3.3.8: Comparison of Laboratory vs. Laboratory-Tensile Strength of Duralcan F3S.30S Sand Mold, As Cast Specimens cast at Duralcan (Foundry C)

	TENSILE STRENGTH-F3S.30S					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-S	318.48	280.13	300.86	15.28	270.91	330.81
Lab. Y, Foundry-C, SF-AC, Mold-S	335.19	271.58	299.71	25.43	249.87	349.55

Table 3.3.9: Comparison of Laboratory vs. Laboratory-Tensile Strength of Lanxide 4040-30P Permanent Mold, Machined Specimens cast at Lanxide (Foundry E)

	TENSILE STRENGTH: 4040-30P					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-E, SF-M, Mold-P	360.12	322.88	341.68	16.14	310.05	373.31
Lab. Y, Foundry-E, SF-M, Mold-P	357.73	308.93	335.27	19.18	297.68	372.86
Lab. Z, Foundry-E, SF-M, Mold-P	376.01	316.58	344.13	20.30	304.34	383.923

The measured tensile strength values from the two laboratories, shown in Table 3.3.10, are significantly different. However, the standard deviation of the data from the two laboratories is almost the same. The mean and lower 95% value of Lab. X data falls outside the lower 95% value of Lab. Y. This observation indicates a significant difference either in the lab practice or in microstructure of the specimens tested by the two laboratories or both.

Table 3.3.10: Comparison of Laboratory vs. Laboratory-Tensile Strength of Lanxide 4040-30P Permanent Mold, Machined Specimens cast at Lanxide (Foundry E)

	TENSILE STRENGTH: 4040-30P					
	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-E, SF-AC, Mold-P	351.51	308.02	321.52	20.44	281.46	361.58
Lab. Y, Foundry-E, SF-AC, Mold-P	378.55	339.87	353.58	18.26	317.79	389.37

3.3.2 Effect of % SiC Content on Tensile Strength:

The effect of % SiC content on the tensile strength is determined using the data for Duralcan alloys F3S.20S and F3S.30S. It is seen from Tables 3.3.11 and 3.3.12 that the tensile strength of specimens with 30% SiC tested machined and in as-cast conditions is lower than that with 20% SiC for specimens tested in the same Lab., cast in the same foundry and using the same process. The standard deviation of the data with 30% SiC is generally higher than those with 20% SiC.

Table 3.3.11: Effect of % SiC on Tensile Strength of Duralcan F3S.20S and F3S.30S alloys Permanent Mold, Machined Specimens cast at Duralcan (Foundry C).

	% SiC	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	20	362.56	318.69	340.70	14.27	312.73	368.67

Lab.-X, Foundry-C, SF-M, Mold-P	30	321.30	283.38	306.44	15.61	275.84	337.04
Lab.-Y, Foundry-C, SF-M, Mold-P	20	365.41	338.15	352.57	9.45	334.05	371.09
Lab.-Y, Foundry-C, SF-M, Mold-P	30	351.42	293.49	320.40	20.32	280.57	360.23
Lab.-Z, Foundry-C, SF-M, Mold-P	20	359.62	310.51	338.13	18.81	301.26	375.00
Lab.-Z, Foundry-C, SF-M, Mold-P	30	321/56	284.99	310.22	17.07	276.76	343.68

Table 3.3.12: Effect of % SiC on Tensile Strength of Duralcan F3S.20S and F3S.30S alloys Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	% SiC	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	20	347.44	323.30	335.07	10.54	314.41	355.73
Lab.-X, Foundry-C, SF-AC, Mold-P	30	340.68	243.74	298.88	38.07	224.26	373.50
Lab.-Y, Foundry-C, SF-AC, Mold-P	20	378.31	348.34	365.89	10.66	345.00	386.78
Lab.-Y, Foundry-C, SF-AC, Mold-P	30	371.53	322.59	339.74	17.58	305.28	374.20

3.3.3 Foundry vs. Foundry: The effect of foundry practice on tensile strength is evaluated using the data for alloy F3S.20S, since specimens for this alloy were cast at two foundries. Tables 3.3.13 and 3.3.14 show that the tensile strength of specimens cast at foundry D is lower than those cast at foundry C using the same casting process, having the same surface finish and tested in the same Lab.

Table 3.3.13: Effect of Foundry on Tensile Strength of Duralcan F3S.20S, Permanent Mold, Machined Specimens.

	Foundry	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	C	362.56	318.69	340.70	14.27	312.73	368.67
Lab.-X, Foundry-D, SF-M, Mold-P	D	338.28	315.98	328.43	9.20	310.40	346.46
Lab.-Y, Foundry-C, SF-M, Mold-P	C	365.41	338.15	352.57	9.45	334.05	371.09
Lab.-Y, Foundry-D, SF-M, Mold-P	D	350.41	330.57	338.90	8.25	322.73	355.07
Lab.-Z, Foundry-C, SF-M, Mold-P	C	359.62	310.51	338.13	18.81	301.26	375.00
Lab.-Z, Foundry-D, SF-M, Mold-P	D	353.68	290.60	331.90	27.37	278.25	385.55

Table 3.3.14: Effect of Foundry on Tensile Strength of Duralcan F3S.20S, Permanent Mold, As Cast Specimens.

	Foundry	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	C	347.44	323.30	335.07	10.54	314.41	355.73
Lab.-X, Foundry-D, SF-AC, Mold-P	D	338.47	309.59	330.16	12.22	306.21	355.73
Lab.-Y, Foundry-C, SF-AC, Mold-P	C	378.31	348.34	365.89	10.66	345.00	386.78
Lab.-Y, Foundry-D, SF-AC, Mold-P	D	363.11	327.18	341.00	14.84	311.91	370.09

3.3.4 Effect of Casting Process-Permanent vs. Sand:

Specimens from alloy Duralcan F3S.30S were cast in 1999 using permanent and sand mold processes. The data generated from those specimens are used in the following tables for comparing the effect of casting process on tensile strength.

The data from Lab. Y, shown in Table 3.3.15, indicates that the casting process may have a slight effect on tensile strength. However, the effect is within the expected experimental error. Hence, it can be concluded that for this alloy the casting process has an insignificant effect on tensile strength.

In Table 3.3.16, it is seen that the as cast specimens indicate that the tensile strength of permanent mold specimens is higher than that of sand mold. Since, the amount of data available for analysis is small, it cannot be concluded that the casting process has a significant effect.

Table 3.3.15: Effect of Casting Process-Permanent vs. Sand on Tensile Strength of Duralcan F3S.30S, Machined Specimens, cast at Foundry C

	Casting Process	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	P	321.30	283.38	306.44	15.61	275.84	337.04
Lab.-X, Foundry-C, SF-M, Mold-S	S	319.94	291.71	305.46	11.19	283.53	327.39
Lab.-Y, Foundry-C, SF-M, Mold-P	P	351.42	293.49	320.40	20.32	280.57	360.23
Lab.-Y, Foundry-C, SF-M, Mold-S	S	328.95	276.11	310.51	18.82	273.62	347.40
Lab.-Z, Foundry-C, SF-M, Mold-P	P	321.56	284.99	310.22	17.07	276.76	343.68
Lab.-Z, Foundry-C, SF-M, Mold-S	S	320.57	279.08	299.82	17.25	266.01	333.63

Table 3.3.16: Effect of Casting Process-Permanent vs. Sand on Tensile Strength of Duralcan F3S.30S, As Cast Specimens, cast at Foundry C

	Casting Process	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	P	340.68	243.74	298.88	38.07	224.26	373.50
Lab.-X, Foundry-C, SF-AC, Mold-S	S	318.48	280.13	300.86	15.28	270.91	330.81
Lab.-Y, Foundry-C, SF-AC, Mold-P	P	371.53	322.59	339.74	17.58	305.28	374.20
Lab.-Y, Foundry-C, SF-AC, Mold-S	S	335.19	271.58	299.71	25.43	249.87	349.55

3.3.5 Effect of Supplier vs. Supplier on Tensile Strength:

The Duralcan F3S.30S from Duralcan and Lanxide 4040-30P from Lanxide Corp. contain 30 percent of SiC. The data from these two materials are compared in the following tables to determine the effect of suppliers on tensile strength. The data from the three laboratories, shown in Tables 3.3.17 and 3.3.18, indicate that the tensile strength of Lanxide alloy containing the same percentage SiC has higher tensile strength. It may be due to the finer size of particles in Lanxide alloy.

Table 3.3.17: Effect of Supplier-Duralcan, USA vs. Lanxide Corp. on Tensile Strength of alloys F3S.30S and 4040-30P containing 30% SiC, Permanent Mold, Machined Specimens

	Supplier	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	Duralcan	321.30	283.38	306.44	15.61	275.84	337.04
Lab.-X, Foundry-E, SF-M, Mold-P	Lanxide	360.12	322.88	341.68	16.14	310.05	373.31
Lab.-Y, Foundry-C, SF-M, Mold-P	Duralcan	351.42	293.49	320.40	20.32	280.57	360.23
Lab.-Y, Foundry-E, SF-M, Mold-P	Lanxide	357.73	308.93	335.27	19.18	297.68	372.86
Lab.-Z, Foundry-C, SF-M, Mold-P	Duralcan	321.56	284.99	310.22	17.07	276.76	343.68
Lab.-Z, Foundry-E, SF-M, Mold-P	Lanxide	376.01	316.58	344.13	20.30	304.34	383.92

Table 3.3.18: Effect of Supplier-Duralcan, USA vs. Lanxide Corp. on Tensile Strength of alloys F3S.30S and 4040-30P containing 30% SiC, Permanent Mold, As Cast Specimens

	Supplier	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	Duralcan	340.68	243.74	298.88	38.07	224.26	373.50
Lab.-X, Foundry-E, SF-AC, Mold-P	Lanxide	351.51	308.02	321.52	20.44	281.46	361.58
Lab.-Y, Foundry-C, SF-AC, Mold-P	Duralcan	371.53	322.59	339.74	17.58	305.28	374.20
Lab.-Y, Foundry-E, SF-AC, Mold-P	Lanxide	378.55	339.87	353.58	18.26	317.79	389.37

3.3.6 Effect of Surface Finish on Tensile Strength-Machined vs. As Cast:

Laboratories X and Y tested both machined and as cast specimens. Hence the data from these two laboratories is used in evaluating the effect of surface finish on tensile strength of the three alloys. The effect of surface finish is very small and for all practical purposes the data from both laboratories fall within the expected experimental error as shown in Tables 3.3.19 and 3.3.20. The Tables also show that irrespective of casting foundry the surface finish has an insignificant effect on tensile strength.

Table 3.3.19: Effect of Surface Finish-Machined vs. As Cast on Tensile Strength of Duralcan F3S.20S, Permanent Mold Specimens cast at Foundry C

	Surface Finish	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	M	362.56	318.69	340.70	14.27	312.73	368.67
Lab.-X, Foundry-C, SF-AC, Mold-P	AC	347.44	323.30	335.07	10.54	314.41	355.73
Lab.-Y, Foundry-C, SF-M, Mold-P	M	365.41	338.15	352.57	9.45	334.05	371.09
Lab.-Y, Foundry-C, SF-AC, Mold-P	AC	378.31	348.34	365.89	10.66	345.00	386.78

Table 3.3.20: Effect of Surface Finish-Machined vs. As Cast on Tensile Strength of Duralcan F3S.20S, Permanent Mold Specimens cast at Foundry D.

	Surface Finish	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-D, SF-M, Mold-P	M	338.28	315.98	328.43	9.20	310.40	346.46

Lab.-X, Foundry-D, SF-AC, Mold-P	AC	338.47	309.59	330.16	12.22	306.21	355.73
Lab.-Y, Foundry-D, SF-M, Mold-P	M	365.41	338.15	352.57	9.45	334.05	371.09
Lab.-Y, Foundry-D, SF-AC, Mold-P	AC	378.31	348.34	365.89	10.66	345.00	386.78

The results in Table 3.3.21 show that the effect of surface finish is very small and for all practical purposes the data from both laboratories falls within the expected experimental error. However, Lab. X data indicates higher variability in as cast specimens. In as cast specimens (Table 3.3.22), there is slightly higher variability. Tables 3.3.21 and 3.3.22 show that irrespective of the casting process the surface finish has an insignificant effect on tensile strength. In Table 3.3.23, Lab. X data indicates higher variability in as cast specimens.

Table 3.3.21: Effect of Surface Finish-Machined vs. As Cast on Tensile Strength of Duralcan F3S.30S, Permanent Mold Specimens cast at Foundry C

	Surface Finish	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	M	321.30	283.38	306.44	15.61	275.84	337.04
Lab.-X, Foundry-C, SF-AC, Mold-P	AC	340.68	243.74	298.88	38.07	224.26	373.50
Lab.-Y, Foundry-C, SF-M, Mold-P	M	351.42	293.49	320.40	20.32	280.57	360.23
Lab.-Y, Foundry-C, SF-AC, Mold-P	AC	371.53	322.59	339.74	17.58	305.28	374.20

Table 3.3.22: Effect of Surface Finish-Machined vs. As Cast on Tensile Strength of Duralcan F3S.30S, Sand Mold Specimens cast at Foundry C

	Surface Finish	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-S	M	319.94	291.71	305.46	11.19	283.53	327.39
Lab.-X, Foundry-C, SF-AC, Mold-S	AC	318.48	280.13	300.86	15.28	270.91	330.81
Lab.-Y, Foundry-C, SF-M, Mold-S	M	328.95	276.11	310.51	18.82	273.62	347.40
Lab.-Y, Foundry-C, SF-AC, Mold-S	AC	335.19	271.58	299.71	25.43	249.87	349.55

Table 3.3.23: Effect of Surface Finish-Machined vs. As Cast on Tensile Strength Lanxide 4040-30P, Permanent Mold Specimens cast at Foundry E

	Surface Finish	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-E, SF-M, Mold-P	M	360.12	322.88	341.68	16.14	310.05	373.31
Lab.-X, Foundry-E, SF-AC, Mold-P	AC	340.68	243.74	298.88	38.07	224.26	373.50
Lab.-Y, Foundry-E, SF-M, Mold-P	M	357.73	308.93	335.27	19.18	297.68	372.86
Lab.-Y, Foundry-E, SF-AC, Mold-P	AC	378.55	339.87	353.58	18.26	317.79	389.37

3.4 Analysis of Variables Affecting Elastic Modulus:

The test data received from GM, Ford, and Daimler Chrysler in 1999 was analyzed using commercially available statistical software SYSTAN to facilitate the evaluation of variables influencing the elastic modulus. The analysis represented in Tables 2.3.1

through 2.3.23 can be used to determine the effect of testing laboratories, %SiC content, casting foundries, casting process, material suppliers, and surface finish on elastic modulus. The test data was broken up as follows for the above analysis.

1. Laboratory vs. Laboratory
2. Effect of % SiC
3. Foundry vs. Foundry
4. Casting Process: Permanent vs. Sand
5. Supplier vs. Supplier
6. Surface Finish-Machined vs. As Cast

3.4.1: Laboratory vs. Laboratory Comparison:

In tables 3.4.1 to 3.4.10 the elastic modulus data obtained in 1999 from GM (Lab. X), Ford (Lab. Y), and Daimler Chrysler (Lab. Z) are compared to assess the effect of individual laboratory testing practices.

It is seen from Tables 3.4.1 and 3.4.2 that there is some difference in the data collected by three laboratories. The results showed that the mean value of the tensile strength tested at laboratory Y is higher than those tested at laboratories X and Z. However, the standard deviation of the tensile strength of the composites cast at Foundry C and tested at laboratory Y is much higher than that tested at X and Z laboratories.

Table 3.4.1: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.20S Permanent Mold, Machined Specimens cast at Duralcan (Foundry C)

	ELASTIC MODULUS-F3S.20S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-P	99.44	96.37	98.64	1.51	95.68	101.60
Lab-Y, Foundry-C, SF-M, Mold-P	249.01	94.37	130.08	58.74	14.95	245.21
Lab-Z, Foundry-C, SF-M, Mold-P	157.73	89.32	116.39	24.14	69.08	163.70

Table 3.4.2: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.20S Permanent Mold, Machined Specimens, cast at ECK Industries (Foundry D)

	ELASTIC MODULUS-F3S.20S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-D, SF-M, Mold-P	101.29	97.67	99.69	1.35	97.04	102.34
Lab-Y, Foundry-D SF-M, Mold-P	129.05	105.66	112.05	8.71	94.98	129.12
Lab-Z, Foundry-D, SF-M, Mold-P	112.64	85.62	97.97	10.66	77.08	118.86

Table 3.4.3 shows that the difference in the data of as cast samples is smaller than these for machined specimens in Table 3.4.1. However, it is significant that the Lab. Y shows considerable variability in the data collected. A similar tendency can be seen from Table

3.4.4 that the difference in the data of as cast samples is smaller than these for machined specimens in Table 3.4.2.

Table 3.4.3: Comparison of Laboratory vs. Laboratory Elastic Modulus of Duralcan F3S.20S Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	ELASTIC MODULUS-F3S.20S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-P	99.31	92.48	96.01	2.63	90.86	101.16
Lab-Y, Foundry-C, SF-AC, Mold-P	159.60	102.15	123.34	21.09	82.00	164.68

Table 3.4.4: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.20S Permanent Mold, As Cast Specimens cast at Duralcan (Foundry D).

	ELASTIC MODULUS-F3S.20S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-D, SF-AC, Mold-P	98.63	93.09	95.04	2.23	90.67	99.41
Lab-Y, Foundry-D, SF-AC, Mold-P	111.40	95.33	99.88	6.52	87.10	112.66

It is seen from Table 3.4.5 that there is a significant difference in elastic modulus data collected by three laboratories. Also, there is a very high variability in data obtained by Lab. Y and Lab. Z. These observations indicate significantly different laboratory practices in collecting elongation data since the tensile strength data does not show such a large variation. This conclusion is based upon the fact that the elastic modulus depends on stress and strain (elongation) within the elastic range of stress-strain data.

Table 3.4.5: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.30S Permanent Mold, Machined Specimens cast at Duralcan (Foundry C)

	ELASTIC MODULUS-F3S.30S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-P	117.54	112.15	114.47	1.95	110.65	118.29
Lab-Y, Foundry-C, SF-M, Mold-P	175.20	111.30	132.07	22.53	87.91	176.23
Lab-Z, Foundry-C, SF-M, Mold-P	158.83	112.54	137.43	24.15	90.10	184.76

Table 3.4.6 shows that there is a significant difference in elastic modulus data collected by the two laboratories. In some cases, the variability is beyond any experimental error and seems to point towards grossly erroneous elongation data.

The results of the elastic modulus of A356-30% SiC composites and A4040-30% SiC composites (Table 3.4.7 through 3.4.10) show that there is not only significant difference in the data collected by the labs.

Table 3.4.6: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.30S Sand Mold, Machined Specimens cast at Duralcan (Foundry C)

	ELASTIC MODULUS-F3S.30S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-M, Mold-S	113.58	112.49	112.90	0.59	111.74	114.06
Lab-Y, Foundry-C, SF-M, Mold-S	135.38	104.56	118.61	12.54	94.03	143.19
Lab-Z, Foundry-C, SF-M, Mold-S	176.86	94.84	134.64	31.25	73.39	195.89

Table 3.4.7: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.30S Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	ELASTIC MODULUS-F3S.30S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-P	115.63	111.12	113.42	1.83	109.83	117.01
Lab-Y, Foundry-C, SF-AC, Mold-P	196.29	48.94	105.93	52.27	3.48	208.38

Table 3.4.8: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Duralcan F3S.30S Sand Mold, As Cast Specimens cast at Duralcan (Foundry C).

	ELASTIC MODULUS-F3S.30S					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-C, SF-AC, Mold-S	113.45	111.19	112.50	0.58	110.25	114.75
Lab-Y, Foundry-C, SF-AC, Mold-S	213.27	88.65	149.87	40.89	69.73	230.01

Table 3.4.9: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Lanxide 4040-30P Permanent Mold, Machined Specimens cast at Lanxide (Foundry E)

	ELASTIC MODULUS: 4040-30P					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-E, SF-M, Mold-P	117.89	114.81	116.33	1.26	113.86	118.80
Lab-Y, Foundry-E, SF-M, Mold-P	194.19	127.50	152.73	22.14	109.34	196.12
Lab-Z, Foundry-E, SF-M, Mold-P	122.05	108.03	115.47	2.36	104.10	126.84

Table 3.4.10: Comparison of Laboratory vs. Laboratory-Elastic Modulus of Lanxide 4040-30P Permanent Mold, As Cast Specimens, cast at Lanxide (Foundry E).

	ELASTIC MODULUS: 4040-30P					
	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab. X, Foundry-E, SF-AC, Mold-P	117.07	112.83	115.56	1.87	111.89	119.23
Lab-Y, Foundry-E, SF-AC, Mold-P	416.77	85.56	192.70	75.56	-103.51	488.91

3.4.2 Effect of %SiC Content on Elastic Modulus:

The effect of % SiC content on elastic modulus is determined using the data for Duralcan alloys F3S.20S and F3S.30S.

It is seen from Tables 3.4.11 and 3.4.12 that the mean value of the elastic modulus of specimens with 30% SiC is higher than that with 20% SiC for specimens tested in the same Lab., cast in the same foundry, using the same process and having the same surface finish. The effect is higher in the data from Lab. X and Lab. Z. It seems that the high variability in the data from Lab. Y for alloy F3S.20S points towards the testing practice used in that laboratory and/or calibration of measuring the instrument system.

Table 3.4.11: Effect of % SiC on Elastic Modulus of Duralcan F3S.20S and F3S.30S alloys, Permanent Mold, Machined Specimens cast at Duralcan (Foundry C).

	% SiC	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	20	99.44	96.37	98.64	1.51	95.68	101.60
Lab.-X, Foundry-C, SF-M, Mold-P	30	117.54	112.15	114.47	1.95	110.65	118.29
Lab.-Y, Foundry-C, SF-M, Mold-P	20	249.01	94.37	130.08	58.74	14.95	245.21
Lab.-Y, Foundry-C, SF-M, Mold-P	30	175.20	111.30	132.07	22.53	87.91	176.23
Lab.-Z, Foundry-C, SF-M, Mold-P	20	157.73	89.32	116.39	24.14	69.08	163.70
Lab.-Z, Foundry-C, SF-M, Mold-P	30	158.83	112.54	137.43	24.15	90.10	184.76

Table 3.4.12: Effect of % SiC on Elastic Modulus of Duralcan F3S.20S and F3S.30S alloys Permanent Mold, As Cast Specimens cast at Duralcan (Foundry C).

	% SiC	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	20	99.31	92.48	96.01	2.63	90.86	101.16
Lab.-X, Foundry-C, SF-AC, Mold-P	30	115.63	111.12	113.42	1.83	109.83	117.01
Lab.-Y, Foundry-C, SF-AC, Mold-P	20	159.60	102.15	123.34	21.09	82.00	164.68
Lab.-Y, Foundry-C, SF-AC, Mold-P	30	196.29	48.94	105.93	52.27	3.48	208.38

3.4.3 Foundry vs. Foundry:

The effect of foundry practice on elastic modulus is evaluated using the data for alloy F3S.20S, since specimens for this alloy were cast at two foundries.

It is seen from Tables 3.4.13 and 3.4.14 that, in general, specimens cast at Foundry D have slightly lower elastic modulus. However, the data for specimens cast at foundry D have lower variability than those cast at foundry C, which is indicative of the difference in casting practice of the two foundries.

Table 3.4.13: Effect of Foundry on Elastic Modulus of Duralcan F3S.20S Permanent Mold, Machined Specimens

	Foundry	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	C	99.44	96.37	98.64	1.51	95.68	101.60
Lab.-X, Foundry-D, SF-M, Mold-P	D	101.29	97.67	99.69	1.35	97.04	102.34
Lab.-Y, Foundry-C, SF-M, Mold-P	C	249.01	94.37	130.08	58.74	14.95	245.21
Lab.-Y, Foundry-D, SF-M, Mold-P	D	129.05	105.66	112.05	8.71	94.98	129.12
Lab.-Z, Foundry-C, SF-M, Mold-P	C	157.73	89.32	116.39	24.14	69.08	163.70

Lab-Z, Foundry-C, SF-M, Mold-P	D	112.64	85.62	97.97	10.66	77.08	118.86
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Table 3.4.14: Effect of Foundry on Elastic Modulus of Duralcan F3S.20S Permanent Mold, As Cast Specimens

	Foundry	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	C	99.31	92.48	96.01	2.63	90.86	101.16
Lab.-X, Foundry-D, SF-AC, Mold-P	D	98.63	93.09	95.04	2.23	90.67	99.41
Lab.-Y, Foundry-C, SF-AC, Mold-P	C	159.60	102.15	123.34	21.09	82.00	164.68
Lab.-Y, Foundry-D, SF-AC, Mold-P	D	111.40	95.33	99.88	6.52	87.10	112.66

3.4.4 Effect of Casting Process-Permanent vs. Sand:

The following tables show the comparing effects of casting process (permanent and sand) on elastic modulus.

It is seen from Table 3.5.15 that the data from Lab. Y and Lab. Z indicate that the casting process has an effect on elastic modulus. However, the effect is contradictory, since the data from Lab. Y shows that permanent mold has higher elastic modulus while the data from Lab. Z indicates that the sand mold has higher elastic modulus. This seemingly contradictory observation leads to believe that there is a large difference in individual lab testing practices.

Table 3.4.15: Effect of Casting Process-Permanent vs. Sand on Elastic Modulus of Duralcan F3S.30S, Machined Specimens, Cast at Foundry C

	Casting Process	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	P	117.54	112.15	114.47	1.95	110.65	118.29
Lab.-X, Foundry-C, SF-M, Mold-S	S	113.58	112.49	112.90	0.59	111.74	114.06
Lab.-Y, Foundry-C, SF-M, Mold-P	P	175.20	111.30	132.07	22.53	87.91	176.23
Lab.-Y, Foundry-C, SF-M, Mold-S	S	135.38	104.56	118.61	12.54	94.03	143.19
Lab.-Z, Foundry-C, SF-M, Mold-P	P	158.83	112.54	137.43	24.15	90.10	184.76
Lab.-Z, Foundry-C, SF-M, Mold-S	S	176.86	94.84	134.64	31.25	73.39	195.89

Table 3.4.16: Effect of Casting Process-Permanent vs. Sand on Elastic Modulus of Duralcan F3S.30S, As Cast Specimens, Cast at Foundry C

	Casting Process	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	P	115.63	111.12	113.42	1.83	109.83	117.01
Lab.-X, Foundry-C, SF-AC, Mold-S	S	113.45	111.19	112.50	0.58	110.25	114.75
Lab.-Y, Foundry-C, SF-AC, Mold-P	P	196.29	48.94	105.93	52.27	3.48	208.38
Lab.-Y, Foundry-C, SF-AC, Mold-S	S	213.27	88.65	149.87	40.89	69.73	230.01

Table 3.4.16 that the data from Lab. X show negligible difference in elastic modulus, indicating that the casting process has no effect, while the data from Lab. Y indicates that the casting process does affect elastic modulus.

3.4.5 Effect of Supplier vs. Supplier on Elastic Modulus: The Duralcan F3S.30S from Duralcan, and Lanxide 4040-30P from Lanxide contain 30 percent of SiC. The data from these two materials are compared in the following tables to determine the effect of suppliers on elastic modulus.

Table 3.4.17: Effect of Supplier-Duralcan vs. Lanxide. on Elastic Modulus of alloys F3S.30S and 4040-30P containing 30% SiC, Permanent Mold, Machined Specimens

	Supplier	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	Duralcan	117.54	112.15	114.47	1.95	110.65	118.29
Lab.-X, Foundry-E, SF-M, Mold-P	Lanxide	117.89	114.81	116.33	1.26	113.86	118.80
Lab.-Y, Foundry-C, SF-M, Mold-P	Duralcan	175.20	111.30	132.07	22.53	87.91	176.23
Lab.-Y, Foundry-E, SF-M, Mold-P	Lanxide	194.19	127.50	152.73	22.14	109.34	196.12
Lab.-Z, Foundry-C, SF-M, Mold-P	Duralcan	158.83	112.54	137.43	24.15	90.10	184.76
Lab.-Z, Foundry-E, SF-M, Mold-P	Lanxide	122.05	108.03	115.47	2.36	104.10	126.84

It is seen from Table 3.4.17 that the data from Lab. X indicate that there is no effect while the data from Lab. Y and Lab. Z indicate that the supplier does affect elastic modulus. However, the Lab. Y and Lab. Z data leads to contradictory conclusion.

Table 3.4.18: Effect of Supplier-Duralcan, USA vs. Lanxide Corp. on Elastic modulus of alloys F3S.30S and 4040-30P containing 30% SiC, Permanent Mold, As Cast Specimens

	Supplier	Maximum MPa	Minimum MPa	Mean MPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-AC, Mold-P	Duralcan	115.63	111.12	113.42	1.83	109.83	117.01
Lab.-X, Foundry-E, SF-AC, Mold-P	Lanxide	117.07	112.83	115.56	1.87	111.89	119.23
Lab.-Y, Foundry-C, SF-AC, Mold-P	Duralcan	196.29	48.94	105.93	52.27	3.48	208.38
Lab.-Y, Foundry-E, SF-AC, Mold-P	Lanxide	416.77	85.56	192.70	75.56	-103.51	488.91

It is seen that the data from Lab. X indicate that there is no effect, while the data from Lab. Y indicate that there is a significant effect of supplier on elastic modulus. However, it seems that there is an error in collection of elongation data by Lab. Y in order to obtain negative lower 95% limit, which is practically impossible. The variability in data collected by Lab. Y is extremely high, which leads to believe that the extensometer that measures elongation was either out of calibration or the calibration data entered in the computer was grossly wrong.

3.4.6 Effect of Surface Finish on Tensile Strength-Machined vs. As Cast:

Laboratories X and Y tested both machined and as cast specimens. Hence the data from these two laboratories are used in evaluating the effect of surface finish on elastic modulus.

It is seen from Tables 3.4.19 through 3.4.23 that the Lab. X data indicate that there is no effect of surface finish, while the data from Lab. Y indicate that there is a significant effect of surface finish on elastic modulus. However, it seems that there is an erroneous error in collection of elongation data by Lab. Y in order to obtain negative lower 95% limit, which is practically impossible. The variability in data collected by Lab. Y is extremely high, which leads us to believe that the extensometer that measures elongation was either out of calibration or the calibration data entered in the computer was grossly wrong.

Table 3.4.19: Effect of Surface Finish-Machined vs. As Cast on Elastic Modulus
Duralcan F3S.20S, Permanent Mold Specimens cast at Foundry C

	Surface Finish	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	M	99.44	96.37	98.64	1.51	95.68	101.60
Lab.-X, Foundry-C, SF-AC, Mold-P	AC	99.31	92.48	96.01	2.63	90.86	101.16
Lab.-Y, Foundry-C, SF-M, Mold-P	M	249.01	94.37	130.08	58.74	14.95	245.21
Lab.-Y, Foundry-C, SF-AC, Mold-P	AC	159.60	102.15	123.34	21.09	82.00	164.68

Table 3.4.20: Effect of Surface Finish-Machined vs. As Cast on Elastic Modulus of
Duralcan F3S.20S, Permanent Mold Specimens, Cast at Foundry D

	Surface Finish	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-D, SF-M, Mold-P	M	101.29	97.67	99.69	1.35	97.04	102.34
Lab.-X, Foundry-D, SF-AC, Mold-P	AC	98.63	93.09	95.04	2.23	90.67	99.41
Lab.-Y, Foundry-D, SF-M, Mold-P	M	129.05	105.66	112.05	8.71	94.98	129.12
Lab.-Y, Foundry-D, SF-AC, Mold-P	AC	111.40	95.33	99.88	6.52	87.10	112.66

Table 3.4.21: Effect of Surface Finish-Machined vs. As Cast on Elastic Modulus of
Duralcan F3S.30S, Permanent Mold Specimens, Cast at Foundry C

	Surface Finish	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-P	M	117.54	112.15	114.47	1.95	110.65	118.29
Lab.-X, Foundry-C, SF-AC, Mold-P	AC	115.63	111.12	113.42	1.83	109.83	117.01
Lab.-Y, Foundry-C, SF-M, Mold-P	M	175.20	111.30	132.07	22.53	87.91	176.23
Lab.-Y, Foundry-C, SF-AC, Mold-P	AC	196.29	48.94	105.93	52.27	3.48	208.38

Table 3.4.22: Effect of Surface Finish-Machined vs. As Cast on Elastic Modulus of
Duralcan F3S.30S, Sand Mold Specimens, Cast at Foundry C

	Surface Finish	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-C, SF-M, Mold-S	M	113.58	112.49	112.90	0.59	111.74	114.06
Lab.-X, Foundry-C, SF-AC, Mold-S	AC	113.45	111.19	112.50	0.58	110.25	114.75
Lab.-Y, Foundry-C, SF-M, Mold-S	M	135.38	104.56	118.61	12.54	94.03	143.19
Lab.-Y, Foundry-C, SF-AC, Mold-S	AC	213.27	88.65	149.87	40.89	69.73	230.01

Table 3.4.23: Effect of Surface Finish-Machined vs. As Cast on Elastic Modulus of Lanxide 4040-30P, Permanent Mold Specimens, Cast at Foundry E

	Surface Finish	Maximum GPa	Minimum GPa	Mean GPa	Standard Deviation	95% Lower	95% Upper
Lab.-X, Foundry-E, SF-M, Mold-P	M	117.89	114.81	116.33	1.26	113.86	118.80
Lab.-X, Foundry-E, SF-AC, Mold-P	AC	117.07	112.83	115.56	1.87	111.89	119.23
Lab.-Y, Foundry-E, SF-M, Mold-P	M	194.19	127.50	152.73	22.14	109.34	196.12
Lab.-Y, Foundry-E, SF-AC, Mold-P	AC	416.77	85.56	192.70	75.56	-103.51	488.91

3.5 Observations on Tensile Properties of Cast Bars

In section 3.1 and 3.2 tensile properties of bars tested at GM, Ford, and Daimler Chrysler in 1999 and by Daimler Chrysler in 2001 are presented. The bar charts of the data presented in Tables 3.1.1 to 3.1.25 and Tables 3.2.1 to 3.2.11 are shown in Figures 3.1 to 3.2.11. The same scale is used on the vertical axis representing tensile strength to facilitate group-to-group comparison. The following general observations can be made from the aforementioned tables and figures:

1. The tensile strength values measured by Daimler Chrysler in 2001 are similar to the values for the same series of samples reported by GM, Ford, and Daimler Chrysler in 1999.
2. However the elastic modulus values reported by Daimler Chrysler in 2001 are much lower than the values reported earlier by GM, Ford and Daimler Chrysler. There appears to be an error in the measurement of elongation values since the tensile strength values are comparable. This conclusion is based upon the usual practice used in computing the elastic modulus, i.e. Elastic Modulus = (Stress/Strain), and strain being the function of elongation. Daimler Chrysler has been contacted to determine the cause of the lower values. This anomaly points to the need for standardizing the test and measurement methods used in determining the mechanical properties of composite samples.
3. The trends in variability of tensile strength are similar. The tensile strengths of Duralcan 30% SiC composites are in general lower than the tensile strength of Duralcan 20% SiC composite, probably because of the lower ductility in 30% SiC composite caused by larger size SiC particles.
4. In general, the tensile strengths of permanent mold cast tensile bars are higher than those of sand-cast tensile bars.
5. The data indicates a considerable variation in tensile strength values within a given lot of tensile bars of the same composition, cast by the same foundry. It is seen from that the maximum and minimum tensile strength values for a sand-cast sample lot are within ± 3 standard deviations. The maximum and minimum tensile strength values of permanent mold cast sample lot were within ± 2 standard deviations. In general the largest variations were in sand-cast bars of composites containing 30% SiC. The samples having the highest and lowest tensile strengths within a given lot

have been identified and their microstructures and fracture surfaces were studied to determine micro-structural features that lead to higher tensile values.

Figure 3.1.1: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.20S, Cast at Duralcan, Tested at GMPT

Figure 3.1.2: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.20S, Cast at Duralcan Tested at GMPT

Figure 3.1.3: Tensile Strength of Sand Mold, Machined, Duralcan F3S.30S, Cast at Duralcan, Tested at GMPT

Fig. 3.1.4. Tensile strength of permanent mild, machined, Duralcan F3S.30S, cast at Duralcan, Tested at GM.

Figure 3.1.5: Tensile Strength of Permanent Mold, Machined, Lanxide 4040-30P, Cast at Lanxide, Tested at GMPT

Figure 3.1.6: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.20S, Cast at Duralcan, Tested at GMPT

Fig. 3.1.7. Tensile strength of permanent mold, As cast, Lanxide 4040-30P, Cast at Lanxide, Tested at GM.

Figure 3.1.8: Tensile Strength of Sand Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at GMPT

Figure 3.1.9: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at GMPT

Figure 3.1.10: Tensile Strength of Permanent Mold, As Cast, Lanxide 4040-30P, Cast at Lanxide, Tested at GMPT

Figure 3.1.11: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.20S, Cast at Duralcan, Tested at Ford Motor Co.

Figure 3.1.12: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.20S, Cast at ECK Industries, tested at Ford Motor Co.

Figure 3.1.13: Tensile Strength of Sand Mold, Machined, Duralcan F3S.30S, Cast at Duralcan, Tested at Ford Motor Co.

Figure 3.1.14: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, tested at Ford Motor Co.

Figure 3.1.15: Tensile Strength of Permanent Mold, As Cast, Lanxide 4040-30P, Cast at Lanxide, Tested at Ford Motor Co.

Figure 3.1.16: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.20S, Cast at Duralcan, Tested at Ford Motor Co.

Figure 3.1.17: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.20S, Cast at ECK Industries, Tested at Ford Motor Co.

Figure 3.1.18: Tensile Strength of Sand Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at Ford Motor Co.

Figure 3.1.19: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at Ford Motor Co.

Figure 3.1.20: Tensile Strength of Permanent Mold, As Cast, Lanxide 4040-30P, Cast at Lanxide, Tested at Ford Motor Co.

Figure 3.1.21: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.20S, Cast at Duralcan, Tested at Daimler Chrysler

Figure 3.1.22: Tensile Strength of permanent Mold, Machined, Duralcan F3S.20S, Cast at ECK Industries, Tested at Daimler Chrysler

Figure 3.1.23: Tensile Strength of Sand Mold, Machined, Duralcan F3S.30S, Cast at Duralcan, Tested at Daimler Chrysler

Figure 3.1.24: Tensile Strength of Permanent Mold, Machined, Duralcan F3S.30S, Cast at Duralcan, Tested at Daimler Chrysler

Figure 3.1.25: Tensile Strength of Permanent Mold, Machined, Lanxide 4040-30P, Cast at Lanxide Tested at Daimler Chrysler

Figure 3.2.1: Tensile Strength of Sand Mold, As Cast, Duralcan F3S.20S, Cast at Duralcan, Tested at Daimler Chrysler in 2001

Tensile Strength of 2DS Series

Figure 3.2.2: Tensile Strength of Sand Mold, As Cast, Duralcan F3S.20S, Cast at ECK Industries, Tested at Daimler Chrysler in 2001

Tensile Strength of 2CP Series

Figure 3.2.3: Tensile Strength of Permanent Mold, As Cast, Duralcan F3S.20S, Cast at Duralcan, Tested at Daimler Chrysler in 2001

Figure 3.2.4: Tensile Strength of Permanent Mold,, As Cast, Duralcan F3S.20S, Cast at ECK Industries , Tested at Daimler Chrysler in 2001

Tensile Strength of 3CS Series

Figure 3.2.5: Tensile Strength of Sand Mold, As Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at Daimler Chrysler in 2001

Tensile Strength of 1DS Series

Figure 3.2.6: Tensile Strength of Sand Mold, As Cast, Lanxide 4040-30P, Cast at ECK Industries, Tested at Daimler Chrysler in 2001

Figure 3.2.7: Tensile Strength of Sand Mold, As Cast, Lanxide 4040-30P, Cast at Lanxide, Tested at Daimler Chrysler In 2001

Tensile Strength of 4ES Series

Figure 3.2.8: Tensile Strength of Sand Mold, As Cast, Lanxide 1060-30P, Cast at Lanxide, Tested at Daimler Chrysler in 2001

Figure 3.2.9: Tensile Strength of Permanent Mold, AS Cast, Duralcan F3S.30S, Cast at Duralcan, Tested at Daimler Chrysler in 2001

Tensile Strength of 1DP Series

Figure 3.2.10: Tensile Strength of Permanent Mold, As Cast, Lanxide 4040-30P, Cast at ECK Industries, Tested at Daimler Chrysler in 2001

Tensile Strength of 4EP Series

Figure 3.2.11. Tensile Strength of Permant Mold, As Cast , Lanxide 1060-30P, Cast at Lanxide, Tested at Daimler Chrysler in 2001.

3.6 Macrostructure Analysis of the Fractured Surface of Al-SiC Tensile Test Bars

The tensile test bars listed in Table 2-3 were selected to determine the relationship between macrostructure and mechanical properties. It is noted that the table lists low, medium, and highest tensile strength bars from each of the three testing laboratories.

The fracture surface of each bar was cleaned before it was examined using an Optical Stereo Microscope. The images of the macrostructure obtained are presented in Figures 3.6.1 to 3.6.5. The general observations that can be made from these macrostructures are:

1. Several macroscopic defects such as porosity, cracks, and brittle phases were observed on the fractured surfaces of tensile test bars.
2. The fractured surfaces of specimens with highest tensile strength from each group were generally more sound than that of bars with lower tensile strength.
3. The main defects observed were voids, porosity, micro-cracks, and second phases. They served to decrease the mechanical properties.
4. The tensile failures appeared to initiate and propagate from large voids near the surface or from large brittle phase particles. The bars that exhibited both types of defects, had in general the lowest tensile strength than those that showed none of the two defects.
5. It appears that to some extent the variation in mechanical properties can be correlated with the variation in macroscopic defects.

High T. S
338.47 MPa

Medium T. S
328.41 MPa

Low T. S
309.59 MPa

D2P – Duralcan F3S.20S
Permanent mold cast by ECK;
tested by GM.
D2P23: High T. S.
D2P2: Medium T. S.
D2P52: Low T. S.

It can be seen that there are lots of white colored bright second phases on the D2P23 fracture surface; the white bright phases appear to be brittle from their cleavage fracture.

Some voids and porosities can also be found on these fracture surfaces, which appear to be the main sources of the crack initiation.

The fracture surface of the D2P23 appears to be much sounder than the D2P52 from comparison of the optical features. There are more defects near the surface of the D2P52 tensile test bar, which probably decrease the tensile properties of the tensile test bar.

Figure 3.6.1: Macrographs of three D2P tensile bar fracture surface.
($\times 6.7$)

High T.S
347.44 MPa

Medium T.S
335.94 MPa

Low T.S
323.30 MPa

C2P- Duralcan F3S.20S

Permanent mold cast by Duralcan

Tested by GM.

C2P16: High T. S.

C2P19: Medium T. S.

C2P8: Low T. S.

It can be seen that there are some bright white colored second phases on the C2P16 fracture surface, which appear to be brittle from their appearances. The fracture surface also shows other defects such as voids and porosity. The failure appears to have initiated and propagated from a brittle second phase particle near the surface of the tensile test bar.

The bright second phases are also found on the fracture surfaces of the C2P19 and C2P8 specimens. Some voids and porosity can be found on these fracture surfaces, which appears to be the sources of the crack initiation.

The fracture surface of the C2P16 appears to be much sounder than that of C2P8. There appears to be larger defects on the C2P8 fracture surface, especially near the surface of the tensile test bar; these include large porosity, and larger brighter white second phases, which may have decreased the tensile properties of the tensile test bar.

Figure 3.6.2: Macrographs of C2P fracture structure. ($\times 6.7$)

High T. S
351.51 MPa

Medium T. S
317.53 MPa

Low T. S
308.02 MPa

E1P- Lanxide 4040-30P
Permanent mold cast by Lanxide
Tested by GM.

E1P11: High T. S.
E1P55: Medium T. S.
E1P48: LowT. S.

1PE materials contain 30 percent SiC particles. It can be seen from the fracture surface that there are some fine bright white second phases on the fracture surfaces. The fracture surfaces of this composite tensile test bars look relatively flat (as compared to F3S.20S), which suggests that the materials are brittle, and have lower elongation.

The structure of fracture surface of the E1P11 is much sounder than that of E1P48 from comparison of the optical features. There is more porosity on the surface of the E1P48 tensile test bar, especially near the surface of the tensile test bar, which apparently decreases the tensile properties of the tensile test bar.

Surprisingly the fracture surface of E1P55 that has the medium properties is most sound.

Figure 3.6.3: Macrographs of E1P fracture structure. ($\times 6.7$)

High T. S
318.48 MPa

Medium T. S
302.90 MPa

Low T. S
280.13 MPa

C3S- Duralcan F3S.30S
Sand mold cast by Duralcan
Tested by GM.

C3S50: High T. S.
C3S6: Medium T. S.
C3S27: Low T. S.

C3S is sand cast composite, which contains 30 percent SiC particles. It can be seen that there are lots of bright white second phases, voids and porosity, and cracks on the fracture surfaces, which can decrease the mechanical properties of the test bars. The cracks can initiate and propagate from such defects as voids, porosity, microcracks and second phases.

The fracture surface of the C3S50 appears sounder than the C3S27. There are many more defects on the C3S27 fracture surface than that of C3S50. It appears that the failure may have initiated from the defects near the surface of the bar C3S27.

Figure 3.6.4: Macrographs of C3S tensile bar fracture surfaces. ($\times 6.7$)

Medium T. S
283.09 MPa

Low T. S
243.74 MPa

C3P- Duralcan F3S.20S
Permanent mold cast by Duralcan
Tested by GM.

C3P39: Medium T. S.
C3P36: Low T. S.

It can be seen that there are defects including porosity and bright second phases on the 3PC fracture surfaces, which could be the sources of decrease in tensile properties of the samples.

The bright phases are fine and uniformly distributed on the C3P39 fracture surface. There are more voids and porosity on the C3P39 fracture surface than that on C3P36 fracture surface. There is a big void near surface of the tensile bar C3P36 and can be seen on the fracture surface. Apparently the crack initiated from this large void reducing the tensile strength of bar C3P36. In addition the fracture surface of C3P36 shows much larger bright white second phase particles, than seen on the fracture surface of bar C3P39.

Figure 3.6.5: Macrograph of C3P Tensile bars fracture surfaces

3.7 Microstructure Evaluation of Selected Tensile Bars

The microstructure characteristics of the as cast Duralcan (F3S.20S) specimens cast at Duralcan (C2P) and cast at ECK Industries (D2P) and tested at GM were evaluated using image analysis. The specimens selected for the analysis had high, medium, and low tensile strength within each group as shown in the Table 3.7.1. The as cast specimens were selected for analysis, since the previous analysis indicated that statistically there was no difference in mechanical properties of as cast and machined specimens.

Table 3.7.1: Tensile Properties of Bars Selected for Microstructure Evaluation

C2P GM AS CAST					
	Specimen ID	Tensile Strength-MPa	Modulus GPa	Yield Strength-MPa	% Elongation
High	2PC16	347.44	93.16	331.94	0.35
Medium	2PC19	335.97	97.12	N/A	0.17
Low	2PC8	323.33	92.48	N/A	0.15
D2P GM AS CAST					
	Specimen ID	Tensile Strength-MPa	Modulus GPa	Yield Strength-MPa	% Elongation
High	2P23	338.49	93.09	320.87	0.38
Medium	2PD2	328.39	98.63	323.13	0.24
Low	2PD52	309.60	95.21	N/A	0.12

3.7.1: Specimen Preparation for Microstructure Evaluation

Each of the six specimens listed in Table 3.7.1 was longitudinally cross-sectioned through the fracture origin using a Buehler 2000 high speed precision cutoff saw. One of the two halves of each specimen was ultrasonically cleaned for one minute. The specimens were then hot mounted in epoxy and auto-polished using the procedure as given in Table 3.7.2. The microstructure of polished specimens was then evaluated in the un-etched condition using a low power Nikon Steroscope and a Zeiss Optical Light Microscope. Quantitative image analysis was performed using a Media Cybernatics Image Pro Analyzer and a Sony RGB CCD camera capable of capturing a 640x480 pixel digital image. The volume fraction of porosity was determined at a magnification of 46X and the average of fifteen fields of view was reported. More recent work on image analysis has been done using the Clemex Image Analysis equipment.

3.7.2: Low Power Evaluation of Microstructure

Low power microphotographs of the fracture surface region of the six samples are shown in Figures 3.7.1 and 3.7.2. It is seen from figures 3.7.1c and 3.7.2c that the specimens

D2P52 and C2P8 with low tensile strength within their respective group, contain large quantities of shrinkage/gas porosity. The porosity was observed both near the fracture surface and as well as in regions away from it. The specimens with high and low tensile strengths comparatively showed less porosity. It is seen from Tables 3.7.3 and 3.7.4 that here is very small difference in level of porosity in specimens with high and medium strengths. Also the porosity within these specimens was randomly distributed. It is not uncommon to find porosity in cast samples since it is inherently associated with the casting process. However, the concentrated localized porosity observed in samples with low tensile strength is of great concern since they seem to lower the tensile strength and accelerate the initiation and progression of failure.

Table 3.7.2: Polishing Procedure

Surface	Abrasive	Head Rotation	Speed RPM	Time Seconds	Force Pounds
SiC Paper	320 Grit	Contra	100	15	3/Sample
SiC Paper	600 Grit	Contra	200	15	5/Sample
Ultra Pad	9 μ Oil	Contra	120	120	5/Sample
Texmet	3 μ Oil	Comp	150	120	5/Sample
Texmet	1 μ Oil	Comp	150	120	5/Sample
Chemomet	0.06 μ Colloidal SiC	Comp	100	90	2.5/Sample

Table 3.7.3: Measured Density and Calculated Porosity

Tensile Strength	Low	Medium	High	Low
Sample ID	C2P8	C2P19	C2P16	D2P52
Density-g/cm ²	2.7536	2.7593	2.7598	2.7510
Porosity-%	0.60	0.39	0.37	0.69
Theoretical Density- g/cm ²	2.77 Per Duralcan F3S.20S Specification			

Table 3.7.4: Volume Fraction Porosity (%) Measured by Image Analysis

Tensile Strength	Low	Medium	High	Low	Medium	High
Sample ID	D2P52	D2P2	D2P23	C2P8	C2P19	C2P16
Minimum	0.1927	0.4463	0.1006	0.1090	0.2126	0.2346
Maximum	9.5475	2.7098	1.6781	12.3193	4.7656	2.4696
Mean	2.8881	1.1018	0.7781	3.0043	1.1667	0.8791
Std. Dev.	2.7899	0.6279	0.4425	3.0314	0.9270	0.5925
Sum	63.54	23.14	13.23	48.07	26.83	19.34
No. of Samples	22	21	17	16	23	22

3.7.3: Optical Evaluation of Microstructure

The microstructures obtained from the Zeiss Optical Light Microscope are shown in Figures 3.7.3 through 3.7.8. It is seen that the preferential path for crack propagation is through the particle/matrix interface. The initiation of failure is usually at the SiC particle/matrix interface with void growth and coalescence followed by a mechanism of ductile tearing through the matrix. Minor evidence of particle cracking can be seen in specimen D2P23 and C2P8. The micro-photographs show preference for the crack through SiC/Al interface, and also the presence of porosity and some fractured and aggregated SiC particles near the fracture surface.

3.7.4 Porosity Measurement using Image Analysis

The densities calculated using the buoyancy method and the theoretical density from Duralcan F3S.20S specification are shown in Table 3.7.3. The calculated porosity is also given. In Table 3.7.4 the quantitative porosity volume fraction measured using the Image analysis is tabulated for all the six specimens. It is seen from these two tables that the low tensile strength exhibited by specimen D2P52 and C2P8 may be associated with the high level of porosity observed in them. Both methods of porosity measurement lead to this conclusion.

The following general observations can be made from the microstructure evaluation presented above.

1. The microstructure analysis seems to indicate that preferentially the fracture surface follows the SiC/Al interface. This may be due to SiC particle de-cohesion; a mechanism initiated by void nucleation, void growth, and coalescence at the SiC particle interface followed simultaneously by a mechanism of ductile tearing through the matrix.
2. It seems that the low tensile strength exhibited by specimens C2P8 and D2P52 may be associated with the high levels of casting defects such as shrinkage/gas porosity and inclusions near the fracture origin. The large level of porosity observed in these specimens most likely accelerated the void nucleation, growth and the coalescence process.
3. The casting defects observed in specimens with medium and high tensile strength were not distinguishable from each other, i.e., they looked very similar.
4. Quantitative image analysis indicated that generally high tensile strength is associated with high density and low level of porosity, while the low tensile strength is associated with low density and high level of porosity. However there are some observations which do not show this correlation.

a.C2P16
High T.S: 341.5 MPa
Un- etched

b.C2P19
Medium T.S: 327.8 MPa
Un-etched

c.C2P19
Medium T.S: 327.8 MPa
Un-etched

Fig. 3.7.1:Porosity-GM as Cast: D2P (15X)

The macrograph shows the casting defects (dark black regions) predominantly shrinkage/gas porosity and some oxide inclusions.

The low T.S sample shows the largest volume fraction of casting defects

a.D2P23
High T.S: 348.3 MPa
Un-etched

b.D2P2
Medium T.S: 334.7 MPa
Un-etched

c.D2P52
Low T.S: 321.0 MPa
Un-etched

Fig. 3.7.2: Porosity-GM as Cast
C2P (15X)

The macrograph shows the casting defects (dark black regions) predominantly shrinkage/gas porosity and some oxide inclusions. The low T.S. sample shows the largest volume fraction of casting defects

a. 106X

b. 412X

Figure 3.7.3 Microstructure GM C2P16 As-Cast – High T.S. 347.4 MPa , Un-etched

Micrographs a and b show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles which indicate de-cohesion of the SiC particles (gray arrows)

a. 106X

b. 412X

Figure 3.7.4: Microstructure GM C2P19 As-Cast – Medium T.S.: 335.97 MPa, Un-etched Micrographs a) and b) show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles. The black regions in (a) are shrinkage porosity. The arrows show de-cohesion of the SiC particles.

a. 106X

b. 412X

Figure 3.7.5: Microstructure GM C2P8 As-Cast – Low T.S.:323.3 MPa, Un-etched

Micrographs a) and b) show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles that indicates de-cohesion of the SiC particles (white arrows). The black regions in (a) are shrinkage porosity. The black arrows show cracked SiC particles perpendicular to the tensile stress. The long arrow shows a shrinkage region with smooth surfaces unlike the remainder of the fracture that is rough

a. 106X

b. 412X

Figure 3.7.6: Microstructure GM D2P23 As-Cast – High T.S.: 338.49 MPa Un-etched Micrographs a) and b) show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles that indicates de-cohesion of the SiC particles (arrows). The black arrow shows a cracked SiC particles perpendicular to the tensile stress.

a. 106X

b. 412X

Figure 3.7.7: Microstructure GM D2P2 As Cast – Low T.S: 328.4 MPa , Un-etched

Micrographs a) and b) show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles that indicates de-cohesion of the particles (arrows).

b. 106X

b. 412X

Figure 3.7.8: Microstructure GM D2P52 As Cast – Low T.S.: 309.6 MPa , Un-etched

Micrographs a) and b) show the microstructure adjacent to the fracture surface. The fracture propagated along the silicon carbide particles that indicates de-cohesion of the particles (arrows). The black regions are shrinkage porosity

3.8 SEM Analysis of the Fracture Surface of Al-SiC Tensile Bars Tested at GM

The SEM analysis of fractured surface of selected tensile bars tested at GM was performed at UWM. These bars had high, medium, and low tensile strength within their own group. Details of these bars are tabulated in Table 3.8.1 below.

Table 3.8.1: Details of Broken Tensile Bars Tested at GM and used for SEM Analysis

Specimen ID	SiC Vol. %	Material Supplier	Casting Foundry	Casting Process	Tensile Strength MPa.	Yield Strength MPa	Elastic Modulus GPa
C2P16	20	Duralcan	Duralcan	Permanent	347.44	331.91	93.16
C2P19	20	Duralcan	Duralcan	Permanent	335.94	N/A	97.12
C2P8	20	Duralcan	Duralcan	Permanent	323.30	N/A	92.48
D2P23	20	Duralcan	ECK	Permanent	338.47	320.87	93.09
D2P2	20	Duralcan	ECK	Permanent	328.41	323.13	98.63
D2P52	20	Duralcan	ECK	Permanent	309.59	N/A	95.21
C3P39	30	Duralcan	Duralcan	Permanent	283.09	N/A	111.12
C3P36	30	Duralcan	Duralcan	Permanent	243.71	N/A	115.63
C3S50	30	Duralcan	Duralcan	Sand	318.48	N/A	N/A
C3S6	30	Duralcan	Duralcan	Sand	302.90	N/A	113.45
C3S27	30	Duralcan	Duralcan	Sand	280.13	N/A	111.19
E1P11	30	Lanxide	Lanxide	Permanent	351.51	N/A	117.07
E1P55	30	Lanxide	Lanxide	Permanent	317.53	N/A	112.83
E1P48	30	Lanxide	Lanxide	Permanent	308.02	N/A	116.38

3.8.1 Summary of SEM Analysis of Specimens Listed in Table 3.8.1

Specimen C2P16 (High Tensile Strength, Tested at GM, Duralcan, 20% SiC, permanent mold, cast at Duralcan)

Figure 3.8.1 shows the results of SEM and EDX analysis on the fracture surface of broken tensile bar C2P16. The fracture surfaces show voids, porosity, secondary phases, films, and fractured SiC particles. Figure (a) shows void on the fracture surface of the tensile test bar. Figure (b) shows a fractured SiC particle while the matrix and the particle surface remains in good contact; this suggests that the interface between SiC particle and Al alloy matrix did not de-bond and move apart during the test. Near the surface of the tensile test bar, there is a large second phase particle, which is rich in Mg according to the EDX analysis as shown in Figure (f). Figure (d) shows a big void (about 150 μm) on the fracture surface of the tensile test bar with a particle (50 μm) in the center of the void. Figure (g) is the EDX spectrum examined near the particle on the fracture surface showing relatively high silicon and carbon contents. This suggests that the particle could be SiC with some aluminum diffused into it

Specimen C2P19 (Medium Tensile Strength, Tested at GM, Duralcan, 20% SiC, permanent mold, cast at Duralcan)

The results of SEM and EDX analysis on the fracture surface of tensile bar C2P19 are shown in Figure 3.8.2. SEM pictures show voids, porosity, secondary phases and SiC particles. There are secondary phases on the fracture surface of the tensile test bar as seen in Figure (a) and (b). Figures (c) and (d) show the typical fracture surface of the tensile test bar. It can be seen from the fracture surface that the matrix shows ductile fracture and the SiC particles show feature of brittle fracture. EDX spectrum of matrix area showing Al and Si is shown in Figure (e).

Specimen C2P8 (Lot Tensile Strength, Tested at GM, Duralcan, 20% SiC, permanent mold, cast at Duralcan)

The results of SEM and EDX analysis on the fracture surface of the broken tensile bar C2P8 are shown in Figure 3.8.3. The fracture surface shows defects including voids, and secondary phases. There are few large size (250 x 40 μm) secondary phases on the fracture surface of the tensile test bar, which are strip shaped as seen in Figures (a), (b), (c) and (d). The EDX analysis of the phase surface in Figure (e) indicates that the phase is Mg rich, compared to the EDX spectrum of the matrix shown in the Figure (f). The fracture of the bright phase suggests that it is brittle.

Specimen D2P23 (High Tensile Strength, Tested at GM, Duralcan, 20% SiC, permanent mold, cast at Eck)

The specimen D2P23 was tested at GM in as cast condition. Its tensile strength is the highest in D2P lot. The fracture surfaces show voids, shrinkage porosity and cracks as seen in Figures 3.8.4 (a) to (k). Figure (a) shows a big crack initiating from the surface of the tensile test bar. On the fracture surface, dendrite cells can be observed in some voids suggesting that it is shrinkage porosity as seen in Figure (b). The EDX spectrum examined on this area as shown in Figure (l) shows that there is Al and Si rich phase in the dendrite region. Figure (c) shows the typical fracture surface of the tensile test bar. It appears to be ductile fracture because there are many dimples on the fracture surface. Figure (d) shows a broken SiC particle, which does not appear to be bonded with the matrix. Figure (e) shows a fracture surface in another region. The defects shown in Figure (f) are often found on the fracture surface, which are considered to decrease the mechanical properties of the composites. Some secondary phase particles were found on the fracture surface as seen in the Figures (g) and (h) which appear to be oxides containing Si, Al, and Mg as confirmed by EDX as shown in Figure 4 (o). It look like snowflakes in shape. Figure (i) is a long crack on the fracture surface. Figure (j) shows a broken SiC particle, and Figure (m) is EDX spectrum of the SiC. The crack on the SiC particle may be caused by the stress accumulation near the interface between SiC particle and matrix. Figure (k) shows oxide, containing aluminum on the fracture surface and the EDX spectrum of this area is shown in Figure (n).

Specimen D2P2 (Medium Tensile Strength, Tested at GM, Duralcan, 20% SiC, permanent mold, cast at Eck)

The specimen D2P2 was tested at GM in as cast condition. The fracture surface of broken tensile test bar shows voids, porosity and cracks. The tensile strength of this bar is medium in the D2P lot. Figure 3.8.5 (a) shows the typical fracture surface of the tensile test bar. Figure (b) shows a crack near the surface of the tensile test bar. A big void can be seen in Figure (c). Many SiC particles are cracked on the fracture surface. Figure (d) shows a cracked SiC particle, while Figure 5 (e) shows a void on the fracture surface. Figure 5 (f) shows a crack on the fracture surface. Figures 5 (g) and (h) show large voids and openings on the fracture surface.

Specimen D2P52 (Low Tensile Strength, Tested at GM Duralcan, 20% SiC, permanent mold, cast at Eck)

The specimen D2P52 was tested at GM in as cast condition. The fracture surface shows voids, porosity and unfilled dendrites. The tensile strength of this bar is lowest in the D2P lot. Figure 3.8.6 (a) is the typical fracture surface of the tensile test bar, in which the matrix shows features of ductile fracture. Near the surface of the bar, lots of defects can be observed. Figure (b) shows a large void about 100 microns away from the surface from which crack can easily initiate, decreasing the mechanical properties. Figure (c) shows another void on the fracture surface. Some dendrite cells can be observed in the void on the fracture surface shown on the Figure (d), which contain Si and Al as determined by EDX shown in Figure (j). This is very likely shrinkage porosity without enough liquid available for feeding. Figure (e) shows a SiC particle coated by oxide identified by EDX as seen in Figure (h). It can be seen that Mg content is very high in this area as shown in Figure (j). It is seen from Figure (f) that the crack has probably initiated from the particle. Figure (g) shows a big void near the surface of the tensile test bar. Figure 6 (h) is the EDX spectrum of SiC particle showing magnesium, aluminum in addition to silicon.

Sample C3P39 (Medium Tensile Strength, Tested at GM, Duralcan, 30% SiC, permanent mold, cast at Duralcan)

The tensile bar C3P39 was tested at GM in as cast condition. The fracture surface shows voids, porosity, and secondary phases. The tensile strength of the test bar C3P39 is medium in the tested lot. Figure 3.8.7 (a) shows a large void, while Figure (b) shows large crack on the fracture surface. The voids and cracks may be the main factors responsible for decrease in the mechanical properties. The Figure (c) shows typical fracture surface of the tensile test bar. It can be seen that quite a few of SiC particles were cleaved during the tensile test along the fracture surface because the surface of the SiC particle is parallel to it. The matrix shows ductile fracture surface. Figure (d) shows a cleaved SiC particle on the fracture surface of the tensile test bar. Many steps are found on the cleaved surface of SiC particle.

Specimen C3P36 (Low Tensile Strength, Tested at GM, Duralcan, 30% SiC, permanent mold, cast at Duralcan)

The tensile bar C3P36 was tested at GM in as cast condition. The fracture surface shows voids and secondary phases. The tensile strength of this tensile test bar is lowest in the tested lot. Figure 3.8.8 (a) shows a region containing a big void located near the surface of the tensile test bar. The top part shows the surface of tensile bar and the bottom shows the void in this figure. Figure (b) shows the cylinder like artifacts and voids around them. Figure (c) shows the typical fracture surface of the tensile test bar. It can be seen that lots of SiC particles are embedded in the matrix. The micro cracks initiating from the interface of the SiC and matrix can be seen in Figure (d).

Sample C3S50 (High Tensile Strength, Tested at GM, Duralcan, 30% SiC, sand mold, cast at Duralcan)

The tensile test bar C3S50 was tested at GM in as cast condition. The fracture surface shows voids and cracks. The tensile strength of the bar C3S50 is highest in tested lot. Figure 3.8.9 (a) shows the typical fracture surface of the tensile test bar. It can be seen that the matrix appears to have ductile fracture (dimples), and the SiC particles appear to have brittle fracture. Figure (b) shows a broken SiC particle on the fracture surface. Some micro cracks appear on the SiC surface. A void can be seen in the Figure (c). Figure (d) shows some bubbles and voids on the fracture surface.

Sample C3S6 (Medium Tensile Strength, Tested at GM, Duralcan, 30% SiC, sand mold, cast at Duralcan)

The tensile test bar C3S6 was tested at GM in as cast condition. The fracture surface shows voids, porosity, and cracks. The tensile strength of the bar C3S6 is medium in C3S lot. Figure 3.8.10 (a) shows big spherical voids near the surface of the bar, which are around 600 microns in size. The large number of defects near the surface of the test bar decreases the mechanical properties. Figure (b) shows a complex void near the surface of the tensile test bar. Figure (c) shows the SiC particles on the fracture surface. There are dimples on the fracture surface of the matrix suggesting ductile fracture. Figure (d) shows the typical fracture surface. Figure (e) shows the EDX spectrum of the area containing SiC particle in which the Si content is higher than that in the matrix. EDX spectrum of the matrix is shown in Figure (f).

Sample C3S27 (Low Tensile Strength, Tested at GM, Duralcan, 30% SiC, sand mold, cast at Duralcan)

The tensile test bar C3S27 was tested at GM in as cast condition. The fracture surface shows voids, and cracks. The tensile strength of the bar C3S27 is lowest in the tested lot. Figure 3.8.11 (a) shows voids, cracks and second phases on the fracture surface of the tensile test bar. The defect near the surface decreases the mechanical properties. Figure (b) shows the second phase seen in Figure (a) at a high magnification. The structure of phase appears flat and smooth and it is Si rich according to the EDX analysis shown in

Figure (e). Figure (c) shows the typical fracture surface. Figure (d) shows a big crack about 700 microns in length near the surface on the fracture surface. Figure (f) shows the EDX spectrum of the matrix.

Sample E1P11 (High Tensile Strength, Tested at GM, Lanxide, 30% SiC, permanent mold, cast at Lanxide)

The tensile test bar 1PE11 was tested in as cast condition at GM. The fracture surface contains voids, porosity, secondary phases and cracks. The tensile strength of E1P11 is highest in the tested lot. Figure 3.8.12 (a) shows the typical fracture surface of the tensile test bar. Figure (b) shows the same fracture surface of the bar at high magnification. Figure (c) shows a big spherical void on the fracture surface, which is around 70 microns in size. Figure (d) shows that the interface between SiC and matrix is tightly bound. Oxide was found on the fracture surface as seen in the Figure (e), which is snowflake like in shape. Figure (h) shows the EDX spectrum of the oxide seen in 12 (e). Figure (f) shows a crack on the fracture surface. Figure (g) shows the EDX spectrum of the SiC particle on the fracture surface.

Sample E1P55 (Medium Tensile Strength, Tested at GM, Lanxide, 30% SiC, permanent mold, cast at Lanxide)

The tensile test bar E1P55 was tested in as cast condition at GM. The fracture surface contains voids, porosity, secondary phases and cracks. The tensile strength of E1P55 is medium in the tested lot. Figure 3.8.13 (a) shows spherical porosity and voids on the fracture surface that decreases the mechanical properties, especially the defects near the surface of the tensile test bar. Figure (b) is the typical fracture surface. Figure (c) shows the same area of the fracture surface of the test bar at high magnification. It can be seen from this figure that there are lots of cracked SiC particles. Figure (d) shows a broken SiC particle on the fracture surface.

Sample E1P48 (Low Tensile Strength, Tested at GM, Lanxide, 30% SiC, permanent mold, cast at Lanxide)

The tensile test bar E1P48 was tested in as cast condition at GM. The fracture surface shows voids, porosity, secondary phases and cracks. The tensile strength of E1P48 is lowest in the tested lot. Figure 3.8.14 (a) shows cleaved secondary particle on the fracture surface near a big void. Figure (b) shows a big void on the fracture surface containing several particles. Figure (c) shows the typical fracture surface. Some cracked SiC particles are seen on the fracture surface of broken tensile test bar in Figure (d).

Conclusions

1. Fractures of the tensile test bars show ductile fracture in the matrix and the cleavage fracture in SiC. Unlike completely brittle materials, which exhibit unstable tensile test crack growth (cleavage catastrophic mode), the SiC_p/Al composite specimens failed in a stable manner.

2. Voids were observed on the fracture surfaces of most of the tensile test bars.
3. The SiC particles and matrix appear to be in good contact. Due to the presence of three dimensional stress fields around the SiC particles, secondary cracks perpendicular to the length of the bar on some SiC particles were observed. Cracking of SiC particles was observed very frequently.
4. Defects such as voids, porosity, bubbles, micro-cracks and shrinkage were observed on the fracture surface of the tensile bars. The specimens with the highest, medium, and lowest tensile strengths exhibited the same types of defects; the only difference was in the size and number of defects. Specimens with the lowest tensile strength had larger number of defects than the specimens with the highest tensile strength, especially near the free surface of test bars.
5. Some strip-like phases were found on the fracture surface, which were Mg rich phases determined by EDX. The cleavage surface of the phases indicates that it is brittle in nature, from which cracks easily propagate.
6. Some flake-like oxides were found on the fracture surface of D2P23 specimen. The EDX analysis indicated that they contained Mg, Al, Si and O elements.

(e)

(f)

(g)

Figure 3.8.1: The results of SEM and EDX analysis of broken tensile bar (highest strength, Duralcan, 20% SiC, permanent mold, cast at Duralcan); (a) showing the void on the fracture surface of the tensile test bar, (b) showing a broken SiC particle on the fracture surface, on which a crack was formed. It can be seen that the interface between SiC and matrix is intact even though the particle fractured, (c) showing a second phase near the surface of the tensile test bar, (d) showing a void on the fracture surface, in which there might be a SiC particle, (e) the EDX spectrum of the matrix, (f) the EDX spectrum of the second phase seen in (c). It contains Mg, Al and Si. The Si content in this phase is lower than that in matrix, (g) the EDX spectrum of the SiC in the void shown in (d).

(e)

Figure 3.8.2: The results of SEM and EDX analysis of broken tensile bar (medium strength, Duralcan, 20% SiC, permanent mold, cast at Duralcan); (a) showing the second phase on the fracture surface of the tensile test bar, (b) showing the same second phase as seen in (a) under high magnification, (c) showing the typical fracture surface of the tensile test bar, (d) showing the typical fracture surface of the tensile test bar at low magnification, (e) showing the EDX spectrum of the matrix on the tensile test bar.

(e)

(f)

Figure 3.8.3: The results of SEM and EDX analysis of broken tensile bar (lowest strength, Duralcan, 20% SiC, permanent mold, cast at Duralcan); (a) and (b) showing the second phase on the fracture surface of the tensile test bar, (c) showing the second phase (strip like phase) shown in figure a) and b) , at higher magnification, (d) showing the interface between the second phase (no SiC particles were found in the second phase) and composite, (e) showing Al, Si, and Mg in the EDX spectrum of the second phase present in the Figure (c), (f) showing Al, and Si in the EDX spectrum of the composite present at the bottom of the Figure (d).

Figure 3.8.4: SEM analysis of broken tensile bar 2PD23 (highest strength, Duralcan, 20% SiC, permanent mold, cast at Eck); (a) shows a crack initiating from the surface of the bar. The crack is about 40 microns in width and over 400 microns in length, (b) shows void in the matrix. It can be seen that the dendrite cells have grown into the void from the matrix. It could be shrinkage porosity where there was insufficient liquid feed to the growing dendrites, (c) shows typical fracture surface of the tensile test bar. There is lot of dimples on the surface, and the fracture appears to be ductile although the stress-strain curve of the tensile test bars is brittle. Some particles can be seen in the dimples, (d) shows cleaved particle in the matrix. The particle does not appear to be bonded with the matrix, (e) shows typical fracture surface of the tensile test bar.

Figure 3.8.4: SEM analysis of broken tensile bar (highest strength, Duralcan, 20% SiC, permanent mold, cast at Eck); (f) shows some voids and cracks on the fracture surface; these can decrease the mechanical properties of the tensile test bars, (g) shows some particles on the fracture surface which do not appear to be SiC particles, (h) shows the same particles as in Figure 4 (g) at higher magnifications. From the EDX analysis (Figure (o)), the particles appear to be oxide containing Si, Mg and Al. (i) shows a crack over 100 microns in length on the fracture surface, (j) shows a fractured SiC particle on the fracture surface. It can be seen that the SiC particle is about 10 microns in size, (k) shows a particle which appears to be an oxide containing Al as determined by EDX as shown in (n).

(l)

(m)

Figure 3.8.4 (cont.): The results of EDX analysis of broken tensile bar (highest strength, Duralcan, 20% SiC, permanent mold, cast at Eck); (l) shows the EDX spectrum of dendrite cells as shown in (b). It can be seen that the cells contain Al, Si, and Mg. (m) shows the EDX spectrum of SiC particle as shown in Figure (d).

(n)

(o)

Figure 3.8.4 (cont.): The results of EDX analysis of broken tensile bar (highest strength, Duralcan, 20% SiC, permanent mold, cast at Eck); (n) shows the EDX spectrum of a particle as shown in Figure (k) appears to be an oxide containing Al. (o) shows the EDX spectrum of the particles as shown in Figures (g) and (h), appear to be oxides containing Al, Si, and Mg.

Figure 3.8.5: The results of SEM analysis of broken tensile bar (medium strength, Duralcan, 20% SiC, permanent mold, cast at Eck); (a) shows the typical fracture surface of the tensile test bars, (b) shows the fracture edge on the fracture surface of the tensile test bar, (c) shows a void on the fracture surface, which will decrease the mechanical properties of the composite materials, (d) shows a broken SiC particle on the fracture surface. The crack is about 2 micron in width, (e) shows a void on the fracture surface, which was intersected by a crack.(f) shows a crack on the fracture surface, (g) shows a very wide crack on the fracture surface, in which there are some SiC particles, (h) shows a particle inside a void.

Figure 3.8.5 (cont.)

Figure 3.8.5 (cont.)

Figure 3.8.6: The results of SEM and EDX analysis of broken tensile bar (lowest strength, Duralcan, 20% SiC, permanent mold, cast at Eck), (a) shows the typical fracture surface of the tensile test bar. It can be seen that the fracture is generally ductile, (b) shows a void near the surface of the tensile test bar, which will significantly decrease the mechanical properties, (c) shows voids on the fracture surface of the tensile test bar, (d) shows dendrite cells in the void, which are due to shrinkage due to poor feeding, (e) shows a crack around a particle which is oxide; the crack appears to initiate from the oxide, (f) shows the crack initiated at the oxide on the particle surface, (g) shows a big void near the surface of the tensile test bar, (h) shows the EDX analysis result of the layer on the particle in Figure (e). It can be seen that the phase is Mg rich in composition. (i) shows the EDX analysis of a SiC particle on the fracture surface, (j) shows EDX analysis result of the dendrite cell in Figure (d). It contains Al and Si.

Figure 3.8.6 (cont.)

(h) EDX of a secondary particle near the crack

(i) EDX of a SiC particle

(j) EDX of dendrite cell on fracture surface

Figure 3.8.6 (cont.)

Figure 3.8.7: SEM analysis of broken tensile bar (medium strength, Duralcan, 30% SiC, permanent mold, cast at Duralcan), (a) shows a big void on the fracture surface, which is about 100 micron in size; it can significantly decrease the mechanical properties of the composite, (b) shows the cracks initiated by a big void, (c) shows the typical fracture surface of the tensile test bar. It can be seen that the matrix shows ductile fracture feature, and the SiC shows brittle fracture feature, (d) shows a broken SiC particle, on which there are many steps on the fracture surface of the SiC particle.

Figure 3.8.8: SEM analysis of broken tensile bar (lowest strength, Duralcan, 30% SiC, permanent mold, cast at Duralcan), (a) shows big voids, top is the surface of the tensile test bar, and bottom is the big void. It can be seen that voids are often formed near the surface. The thickness is around 30 micron, (b) shows a defect on the fracture surface. It can be seen that some cylinder shape artifacts are present, (c) shows the typical fracture surface of the tensile test bar, (d) shows micro crack on the fracture surface. It can be seen that the crack initiated from the interface between the SiC particle and matrix.

Figure 3.8.9: SEM analysis of broken tensile bar (highest strength, Duralcan, 30% SiC, sand mold, cast at Duralcan), (a) shows the typical fracture surface of the tensile test bar, (b) shows broken SiC particle on the fracture surface of the tensile test bar showing cracks on the SiC particle, (c) shows void on the fracture surface of the tensile test bar, (d) shows some bubbles and voids near the surface of the tensile test bar.

Figure 3.8.10: SEM analysis of broken tensile bar (medium strength, Duralcan, 30% SiC, sand mold, cast at Duralcan), (a) shows big spherical voids near the surface of the tensile test bar. The bubbles are more than 600 micron in size. Figure (b) shows defects near the surface of the tensile test bar, (c) shows the SiC particles on the fracture surface. The fracture structure of the matrix shows ductile structure (many dimples). Figure (d) shows the typical fracture surface.

(e) EDX of SiC Particle

(f) EDX of the Matrix

Figure 3.8.10 (cont.): EDX analysis of broken tensile bar (medium strength, Duralcan, 30% SiC, sand mold, cast at Duralcan), (e) shows the spectrum of a phase (bright phase on the macro picture). It contains Al and Si. Figure (f) shows the EDX spectrum of the matrix of the composite.

Figure 3.8.11: SEM analysis of broken tensile bar (lowest strength, Duralcan, 30% SiC, sand mold, cast at Duralcan), (a) shows some defects near the surface of the tensile test bar. On the fracture surface there are cracks, bubble and second phases. Figure (b) shows the high magnification of the second phase on the figure (a). The surface of the second phase is flat and smooth, and the fracture surface of the phase looks like brittle structure. Figure (c) shows the typical fracture surface of the tensile test bar, while (d) shows a crack near the surface.

(e)

(f)

Figure 3.8.11 (cont.): EDX analysis of broken tensile bar (lowest strength, Duralcan, 30% SiC, sand mold, cast at Duralcan), (e) shows the spectrum of the phase shown on the figure (b). It contains Si and Al. Figure (f) shows the spectrum of the matrix.

Figure 3.8.12: SEM analysis of broken tensile bar (highest strength, Lanxide, 30% SiC, permanent mold, cast at Lanxide), (a) shows the typical fracture surface of the tensile test bar. Figure (b) shows the high magnification fracture surface of the tensile test bar. Figure (c) shows a big void on the fracture surface of the tensile test bar. It is around 60 microns in size. Figure (d) shows the high magnification fracture surface of the tensile test bar. Figure (e) shows oxide on the fracture surface of the tensile test bar. While (f) shows crack on the fracture surface of the tensile test bar.

(g)

(h)

Figure 3.8.12 (cont.): EDX analysis of broken tensile bar (highest strength, Lanxide, 30% SiC, permanent mold, cast at Lanxide), (g) shows the spectrum of the SiC particle. Figure (h) shows the spectrum of the phase shown on the Figure 12 (e) appearing to be an oxide containing Al, Si, and Mg.

Figure 3.8.13: SEM analysis of broken tensile bar (medium strength, Lanxide, 30% SiC, permanent mold, cast at Lanxide), (a) shows the defects on the fracture surface of the tensile test bar. There are lots of bubbles, voids and porosity on the fracture surface. Figure (b) shows the typical fracture surface of the tensile test bar. Figure (c) shows higher magnification picture of fracture surface of the tensile test bar. It can be seen that lots of SiC particles contain cracks. Figure(d) shows a broken SiC particle.

Figure 3.8.14: SEM analysis of broken tensile bar (lowest strength, Lanxide, 30% SiC, permanent mold, cast at Lanxide), (a) shows a cleaved surface on the fracture surface of the tensile test bar. Figure (b) shows a bubble on the fracture surface of the tensile test bar. It is about 60 microns in size. Figure (c) shows the typical fracture surface of the tensile test bar, while (d) shows the higher amplification of the fracture surface of the tensile test bar. Cracks on the few SiC particles were found on the fracture surface.

Chapter 4. Fatigue Properties of A359-SiC Composites

4.1 Introduction

Particulate reinforced cast Aluminum MMCs are being increasingly developed for many automotive and aerospace applications where fatigue behavior under cyclic loading is important [8-13].

The microstructure of cast composites have a major influence on fatigue properties. In the current study, Al359-20% SiC composites were made using solidification processing and cast in permanent molds. The fatigue samples fabricated from these bars were heat treated to T6 condition and tested at strain levels ranging from 0.1% to 0.3% under strain control conditions. The fracture surfaces of tested specimens were examined using SEM and optical stereo microscopy to identify their fatigue behavior. In addition, image analysis was performed on microstructures away from fracture surface to determine the effect of variation in particle volume fraction in successive fields on the fatigue properties. The current study describes the data generated on fatigue life and analyzes the effect of microstructure on fatigue properties of permanent mold cast A359-20% SiC_p composites heat-treated to T6 condition. The results of this analysis can be used to identify microstructures that are likely to provide high fatigue life.

4.2 Experimental Procedure

4.2.1 Material

Duralcan supplied the material used in this study. The chemical composition of base Al-359 matrix and the F3S.20S MMC alloy was as follows:

Table 4.1. Composition of Al-359

Elements	Cu	Mg	Mn	Si	Fe	Zn	Ti	Others	Bal.
Contents	≤ 0.2	0.5~ 0.7	≤0.10	8.5~9.5	≤ 0.2	≤ 0.10	≤ 0.20	≤ 0.15	Al

Table 4.2: Composition of F3S.20S (20% SiC_p) Alloy

Elements	Cu	Mg	Mn	Si	Fe	Zn	Ti	SiC	Al
Contents	<0.2	.5-.7	<0.1	8.5-9.5	<0.2	<0.2	<0.2	18-22	Rest

The average SiC particle size was in the range of 10-20 μm. The bars from which fatigue specimens were made were cast using permanent mold and heat treated to T6 condition at Eck Industries. Each bar was stamped with a code to identify the material (alloy), casting foundry and the casting process. The coding of the test bars was as follows:

- First letter or digit identified the casting foundry
- Second letter or digit identified the alloy
- Third letter or digit identified the casting process (S for Sand and P for Permanent)
- Last digit or digits identified specimen number

The density measurements and radio-graphical analysis were performed to ensure soundness of the test bars before cutting them into fatigue specimens.

4.2.2 Fatigue Testing

Fatigue tests were performed on F3S.20S (20% SiCp) permanent mold bars cast at Eck Industries. A total of 21 fatigue test samples were machined to the dimensions shown in Fig. 4.1 from the larger bars originally cast in permanent molds for tensile testing. Machining of the fatigue samples as well as fatigue testing of specimens was done at Westmoreland material testing and research, Youngstown PA. Fatigue testing was performed using MTS Electro-Hydraulic test system with 11 Kip load frame, 22 Kip load cell, and the cylinder with 4" stroke. Specimens were tested at room temperature, per ASTM E-606 under fully reversed axial loading with $R = -1$. All the tests were started in strain controlled condition. However, tests at low strain levels, as shown in Table 4.3, were switched to load control, when a specimen reached 43,200 cycles with (a) no plasticity observed in the hysteresis loops, and (b) no change in stress strain magnitudes (stable hysteresis loop). The test frequency was 0.5 Hz under strain- controlled mode and 9 Hz in load control. It was switched to 20 Hz when specimen exceeded 1,000,000 cycles. MTS Model 535 extensometer with gauge length of 6mm (0.25") was used to control the strain range during testing.

All the fatigue test specimens were run to final fracture defined as separation of the specimen into two halves. However failure was defined as the point where the maximum stress amplitude decreased to 50% of the stress at 100 cycles (when fatigue life was greater than 100 cycles). The specimen cyclic stress–strain loops were obtained for cycles 1-10 (in increment of 1), 20-100 (in increment of 10), 200-1000 (in increment of 100), 2000-10000 (in increment of 1,000) and there after in increment of 10,000 until final failure. Hysteresis loops were used for (a) assessing cyclic hardening and softening behavior and (b) calculating stress strain magnitudes at half life.

The specimens tested at the same total strain level were put into one group. The specimens that exhibited a fatigue life ratio of >2 within the same group were selected for SEM analysis to establish relationship between the microstructure and the fatigue life.

A - Length of reduced section; G - Gauge length; D – Diameter
Permanent mold: $A = 1.125''$; $G = .500 \pm 0.005''$; $D = 0.2521 \pm 0.0004''$

Figure 4.1: Dimensions of Fatigue Sample Machined from as Cast Tensile Bar

4.2.3 Fracture Surface Analysis

Fracture surfaces of the composites tested at various strain levels were examined using an optical stereo microscope and a scanning electron microscope (SEM). Fatigue initiation sites, porosity, inclusions, and a fracture pattern were identified for each specimen. Quantification of particle distribution and porosity content in different fields were determined on metallographically polished samples (away from fracture surface) using quantitative image analysis.

4.3 Results and Discussion

4.3.1 Fatigue Testing

Table 3 shows the fatigue test data from the 21 permanent mold specimens cast at ECK industries from Duralcan 20% SiC (D2P series). All the values were calculated from the hysteresis loop taken at Half Life of the specimen.

Table 4.3. Fatigue Test Data Calculated from Hysteresis Loops at Half Life For F3S.20S Alloy Cast at Eck Industries

Specimen ID	Total Strain Range	Total Strain Amplitude	Stress Range (Mpa)	Reversals to Failure (2Nf)	Stress Amp (Mpa)	Elastic Strain Amp	Plastic Strain Amp
D2P53	0.00649	0.003245	592.87	122	296.44	0.002935	0.00031
D2P29	0.00648	0.00324	581.78	146	290.89	0.002865	0.000375
D2P56	0.00599	0.002995	569.18	386	284.59	0.00275	0.000245
D2P45	0.00599	0.002995	566.31	768	283.15	0.002755	0.00024
D2P59	0.006	0.003	547.58	920	273.79	0.002725	0.000275
D2P54	0.00499	0.002495	487.19	1502	243.60	0.002385	0.00011
D2P47	0.00499	0.002495	471.34	3292	235.67	0.002365	0.00013
D2P28	0.005	0.0025	485.54	4526	242.77	0.002395	0.000105
D2P34	0.00399	0.001995	404.91	7454	202.46	0.001945	0.00005
D2P24	0.00399	0.001995	401.32	10666	200.66	0.00195	0.000045
D2P48	0.004	0.002	401.78	22702	200.89	0.00194	0.00006
D2P60	0.003	0.0015	307.56	44936	153.78	0.00149	0.00001
D2P43	0.003	0.0015	301.30	61496	150.65	0.001485	0.000015
D2P36	0.00299	0.001495	303.08	64604	151.54	0.001485	0.00001
D2P7*	0.0025	0.00125	253.69	139420	126.84	0.001245	0.000005
D2P33*	0.0025	0.00125	260.16	193400	130.08	0.001245	0.000005
D2P17*	0.00249	0.001245	260.16	379574	130.08	0.001245	
D2P38*	0.00199	0.000995	208.75	1168636	104.38	0.000995	
D2P58*	0.00199	0.000995	208.75	1493400	104.38	0.000995	
D2P31*	0.00199	0.000995	208.75	2445046	104.38	0.000995	
D2P49*	0.00201	0.001005	210.85	20000000	105.43	0.001005	

* At 43,000 cycles or 86,000 reversals test was switched from strain to load control.

The stress amplitude for the cast Al356-20%SiC composites heat treated to T6 condition was plotted as a function of fatigue life, in Figure 4.3.2. Other published fatigue data is

also shown in the figure for the purpose of comparison. It is seen that the specimens tested ($\blacklozenge$ symbol) have a better fatigue life than the A356-20%SiC composites ($\times$ symbol), but not better than the extruded (Δ symbol) or forged ($\circ$ symbol) composites or Al2080-20% SiC composites ($\diamond$ symbol). In general, cast metal-matrix composites contain various casting defects, such as inclusions and porosity, in addition to microstructural defects like particle clusters and variations in volume percent of SiC particles in neighboring fields. These defects usually act as a source of fatigue initiation sites, resulting in lower fatigue life. The lower fatigue life in some of the Al-20%SiC test specimens in this study appear to be related to the larger casting defects in the test bars.

In Figure 4.2, that the composite tested in this study has a fatigue limit of around 100 MPa, while other composites do not have clear fatigue limit. A359-T6 cast alloy was reported to have the fatigue limit of about 60 MPa at about 10^7 cycles [16]. The presence of SiC particles in aluminum matrix generally increases the strength of composite material, resulting in improved fatigue life as compared to the matrix alloy. It is noted from Figure 4.2 that the rate of increase in the fatigue life with decreasing stress amplitude is similar for three composites- (a) cast Al-20% SiC, (b) forged composites, and (c) extruded composites. However, the cast Al359-20%SiC T6 (D2P Series-material used in this research) composites have a slightly steeper slope than that of the A356-20%SiC (Duralcan). Therefore at low stress amplitude the present composite will have lower fatigue life compared to A356-20%SiC (Duralcan) but at the higher stress amplitude it will have longer life.

Figure 4.2: Stress Amplitude vs. Fatigue Life for Various Composite Materials

It is seen from Tables 4.3 and 4.4 that the fatigue life of the Al359-20%SiC composites made and tested under identical conditions show scatter in fatigue life by a factor of 2 to 3. This variation can be related to factors such as microstructure, particle distribution, particle volume fraction, and casting defects. Examination of fracture surface and

microstructure, including particle distribution, was necessary to identify the factors influencing the fatigue life.

Table 4.4: Fatigue Specimens Pairs for Comparison

Pair No.	Specimen ID	% Total Strain	Fatigue Life	Pair No.	Specimen ID	% Total Strain	Fatigue Life
1	D2P38	0.100	584,318	1	D2P31	0.100	1,222,523
2	D2P7	0.125	69,710	2	D2P17	0.125	189,7
3	D2P60	0.150	22,468	3	D2P36	0.150	32,308
4	D2P34	0.200	3,727	4	D2P48	0.200	11,351
5	D2P54	0.250	751	5	D2P28	0.250	2263
6	D2P56	0.300	193	6	D2P59	0.300	460

4.4: Data Analysis

It was mentioned before that the cyclic stress-strain loops were collected throughout the specimen life. However, the stress-strain data shown in Table 5.3 is summarized from the stable hysteresis loops obtained approximately at the half-life for calculating the fatigue properties. This is according to the procedure recommended in ASTM E606. The elastic and plastic strain amplitudes (ranges) were obtained from the total strain amplitude (range), stress amplitude (range), and elastic modulus as described below.

$$\text{Elastic Strain Amplitude } (\epsilon_e) = \frac{\text{StressAmplitude}(\sigma_a)}{\text{ElasticModulus}(E)} \quad (1)$$

$$\text{Elastic Strain Range} = 2 \times \text{Elastic Strain Amplitude } (2 \times \epsilon_e)$$

The plastic strain amplitude (ϵ_p) was then calculated from the total strain amplitude (ϵ_t) and the elastic strain amplitude (ϵ_e) as shown below.

$$\epsilon_t = \epsilon_e + \epsilon_p \quad (2)$$

4.4.1 Elastic Strain Amplitude vs. Life: The elastic strain amplitude versus fatigue life in reversals ($2 \times N_f$, where N_f is fatigue life in cycles) was plotted on the logarithmic paper as shown in Fig.5.3. The least square line was drawn through the individual data points to obtain the elastic strain-life properties, the Fatigue Strength Exponent (b) – the slope of the above curve and the Fatigue Strength Coefficient (σ_f') – the intercept of the curve at $2N_f = 1$. They are:

$$b = -0.1145 \quad \text{and} \quad \sigma_f' = 0.0055 \times E$$

The elastic strain amplitude at any given life is then given by

$$\epsilon_e = (\sigma_f' / E)(2N_f)^b \quad (3)$$

For the material tested, the elastic strain-life equation is therefore,

$$\varepsilon_e = 0.0055(2N_f)^{-0.1145} \quad (4)$$

4.4.2 Plastic Strain Amplitude vs. Life:

The plastic strain amplitude versus fatigue life in reversals ($2 \times N_f$, where N_f is fatigue life in cycles) was plotted on the logarithmic paper as shown in Fig.4.4. The least square line was drawn through the individual data points to obtain the plastic strain-life properties, the Fatigue Ductility Exponent (c) – the slope of the above curve and the Fatigue Ductility Coefficient (ε_f') – the intercept of the curve at $2N_f = 1$. They are:

$$c = -0.6066 \quad \varepsilon_f' = 0.0108$$

The plastic strain amplitude at any given life is then given by

$$\varepsilon_p = \varepsilon_f' (2N_f)^c \quad (5)$$

For the material tested, the plastic strain-life equation is therefore,

$$\varepsilon_p = 0.0108(2N_f)^{-0.6066} \quad (6)$$

Fig. 4.3: Elastic Strain Amplitude vs. Life Fig. 4.4: Plastic Strain Amplitude vs. Life

Substituting equations (4) and (6) into equation (2), the total strain vs. life equation for the composite tested is given by

$$\varepsilon_t = 0.0055(2N_f)^{-0.1145} + 0.0108 (2N_f)^{-0.6066} \quad (7)$$

Two parts of equation 7 are plotted in Figure 4.5. The sum provides plot of total strain vs. life. At large strain amplitudes the strain-life curve approaches the plastic strain vs. life line and at low strain amplitudes, it approaches the elastic strain vs. life line. The transient life, which is the intersection point of the elastic and the plastic strain life lines, is obtained by equating the elastic strain and the plastic strain amplitude at the intersection point. The transient life can be expressed as follows:

$$2N_t = \left(\frac{\varepsilon_f' E}{\sigma_f'} \right)^{1/(b-c)} \quad (8)$$

Figure 4.5: Transient Life as a Function of Elastic and Plastic Strain

4.4.3 Plastic Strain Amplitude vs. True Stress Amplitude:

The plastic strain amplitude versus true stress amplitude was plotted on the logarithmic paper as shown in Fig. 4.6. The least square line was drawn through individual data points to obtain the Strain Hardening Exponent (n') – the slope of the above curve and the Fatigue Strength Coefficient (K') – the intercept of the curve at $\varepsilon_p = 1$. They are:

$$n' = 0.1960 \quad K' = 1412 \text{ MPa}$$

The plastic strain amplitude for any given stress amplitude is then given by

$$\sigma = K' (\varepsilon_p)^{n'} \quad (9)$$

For the material tested, the plastic strain-true stress amplitude equation is therefore

$$\sigma = 1412 (\varepsilon_p)^{0.196} \text{ MPa} \quad (10)$$

Figure 4.6: True Stress vs. Plastic Strain

4.4.4 Fracture Surface Analysis.

Fatigue cracks in the composites produced by casting generally initiate at defects, such as porosity, inclusions, and voids, which are considered inherent in the cast materials. In the discontinuous reinforced material the de-bonding of the matrix and particles is frequently observed. Failures occur within composites in three ways. They are: (1) weak interfacial strength between particles and matrix propagate the crack through interface, (2) strong interface strength cause cracks to propagate through particles, and (3) a weak matrix favor fracture through the matrix by normal void nucleation and growth. Fracture surfaces of fatigue tested samples in Table 4.3 were analyzed using Optical Stereo Microscope and SEM. The optical micrographs are shown in Figures 4.7 through 4.12. They show the presence of inclusions and porosity on the fracture surfaces, which act as the potential crack nucleation sites. The fracture surface analysis performed using SEM is shown in Figures 4.13 through 4.27. They show the presence of the voids in aluminum matrix. SiC particle fracture was also observed in some of the samples.

Inclusion
400 μm x 200 μm

Probable sites for
Fatigue Crack initiation
Porosity: 700 μm x 400 μm

D2P53
Half Life Strain: 0.33%
Half Life Stress: 296 MPa
Fatigue Life: 61 Cycles

Probable site for
Fatigue Crack initiation
Porosity: 700 μm x 500 μm

D2P29
Half Life Strain: 0.33%
Half Life Stress: 291 MPa
Fatigue Life: 73 Cycles

Fig. 4.7: Optical Stereo Micrograph of Fracture Surfaces (D2P53 and D2P29)

D2P56
 Half Life Strain: 0.30%
 Half Life Stress: 284 MPa
 Fatigue Life: 193 Cycles

Probable Fatigue Crack
 Initiation Site

Inclusion
 200 μ m x 130 μ m

D2P45
 Half Life Strain: 0.30%
 Half Life Stress: 283 MPa
 Fatigue Life: 384 Cycles

Probable Fatigue Crack
 Initiation Site

Inclusion
 400 μ m x 170 μ m

D2P59
 Half Life Strain: 0.30%
 Half Life Stress: 274 MPa
 Fatigue Life: 460 Cycles

Probable Fatigue Crack
 Initiation Site

Figure 4.8: Optical Stereo Micrographs of Fracture Surfaces (D2P56, D2P45 and D2P59)

Figure 4.9: Optical Stereo Microphotographs of Fracture Surface (D2P54, D2P47 and D2P28)

Figure 4.10: Optical Stereo Micrographs of Fracture Surfaces (D2P34, D2P24, and D2P48)

Figure 4.11: Optical Stereo Micrographs of Fracture Surfaces (D2P7, D2P33, and D2P17)

Figure 4.12: Optical Stereo Micrographs of Fracture Surfaces (D2P38, D2P58, and D2P31)

100X

500X

Figure 4.13: SEM Microphotograph of D2P53 Fracture Surface Test Strain: 0.33%, Stress: 296 MPa, Fatigue Life: 61 Cycles

100X

500X

Figure 4.14: SEM Microphotograph of D2P29 Fracture Surface Test Strain: 0.33%, Stress: 291 MPa, Fatigue Life: 73 Cycles

100X

500X

Figure 4.15: SEM Microphotograph of D2P45 Fracture Surface Test Strain: 0.30%, Stress: 283 MPa, Fatigue Life: 384 Cycles

50X

100X

500X

Figure 4.16: SEM Microphotograph of D2P54 Fracture Surface
 Test Strain: 0.25%, Stress: 244 MPa, Fatigue Life: 741 Cycles

100X

500X

Figure 4.17: SEM Microphotograph of D2P47 Fracture Surface
Test Strain: 0.25%, Stress: 236 MPa, Fatigue Life: 1,646 Cycles

100X

100X

500X

Figure 4.18: SEM Microphotograph of D2P28 Fracture Surface
 Test Strain: 0.25%, Stress: 243 MPa, Fatigue Life: 2,263 Cycles

50X

500X

Figure 4.19: SEM Microphotograph of D2P34 Fracture Surface
 Test Strain: 0.20%, Stress: 202 MPa, Fatigue Life: 3,727 Cycles

100X

500X

Figure 4.20: SEM Microphotograph of D2P24 Fracture Surface
Test Strain: 0.20%, Stress: 201 MPa, Fatigue Life: 5,333 Cycles

100X

500X

500X

Figure 4.21: SEM Microphotograph of D2P48 Fracture Surface
 Test Strain: 0.20%, Stress: 201 MPa, Fatigue Life: 11,351 Cycles

100X

500X

100X

500X

Figure 4.22: SEM Microphotograph of D2P43 Fracture Surface
 Test Strain: 0.15%, Stress: 130 MPa, Fatigue Life: 30,748 Cycles

100X

500X

100X

500X

Figure 4.23: SEM Microphotograph of D2P33 Fracture Surface
Test Strain: 0.125%, Stress: 130 MPa, Fatigue Life: 96,700 Cycles

100X

500X

Figure 4.24: SEM Microphotograph of D2P17 Fracture Surface
 Test Strain: 0.125%, Stress: 130 MPa, Fatigue Life: 189,787 Cycles

100X

500X

Figure 4.25: SEM Microphotograph of D2P38 Fracture Surface
Test Strain: 0.10%, Stress: 104 MPa, Fatigue Life: 584,318 Cycles

100X

500X

Figure 4.26: SEM Microphotograph of D2P58 Fracture Surface
 Test Strain: 0.10%, Stress: 104 MPa, Fatigue Life: 746,700 Cycles

100X

500X

Figure 4.27: SEM Microphotograph of D2P31 Fracture Surface
Test Strain: 0.10%, Stress: 104 MPa, Fatigue Life: 1,222,523 Cycles

4.4.5 Comparison of Fracture Surfaces of Fatigue Pairs listed in Table 4.3

Figure 4.12 show optical-stereo micrographs of the fracture surfaces of fatigue specimens D2P38 and D2P31 were tested at the total strain of 0.1%. The optical stereo microphotograph of the D2P38 exhibits large size porosity at the center of the specimen and the D2P31 bar shows a spherical porosity near the surface, which is larger than that seen in the sample D2P38. The two specimen failed at 1,222,523 and 584,328 cycles respectively. The two bars with the same volume fraction of SiC particles exhibited a wide difference in their fatigue life, even though they were tested under identical conditions. The comparison of their fracture surfaces show that they have quite different fracture patterns. The optical stereo microphotograph of the D2P31 specimen (Figure 4.12) shows a pattern suggesting that failure initiated from the large size pore near the surface of the specimen and then progressed through the rest of the matrix. In contrast, such a pattern is not visible in the fracture surface of the D2P31 specimen.

Fatigue cracks tend to form easily on or near the surface of specimens [9,17], where higher stresses are concentrated. In addition, they are prone to initiate at pores and also at the interfaces between the particles and the matrix [18]. The larger size cracks tend to form more readily near larger size pores or defects that dominate fatigue failure. Therefore, the fatigue specimen D2P31, which has a large size pore near the surface, would be expected to have a lower fatigue life than the D2P38. However, the test data show that the result is contrary to the expectation. This observation suggests that the large porosity near the surface of the D2P31 specimen is not the most predominant factor influencing its fatigue life.

Fracture surfaces of the D2P7 and D2P17 fatigue specimens are shown in optical stereo micrographs in Figure 4.11. It was observed that the fatigue life of the D2P7 specimen is shorter (69,710 cycles) than that of the D2P17 specimen (189,787 cycles) at the total strain of 0.125. The examination of the fracture surfaces of the two specimens suggest that in case of D2P7 the crack may have initiated at the defect visible near the bottom left portions of the macro-photographs, resulting in lower fatigue life. The surface of the D2P17 specimen shows that there is no single dominating defect, even though there are multiple visible pores, which seem to have very little or no influence on its fatigue life.

Figures 4.10 show optical stereo photographs of the fracture surfaces of D2P34 and D2P48 fatigue specimens. They were fatigue tested at the total strain level of 0.2%. The D2P34 specimen has a shorter fatigue life (3,727 cycles) than the D2P48 specimen (11,351 cycles). The examination of fracture surface of the specimen D2P48 shows that there are several striations oriented in the direction of the fatigue crack. However, the D2P34 fatigue specimen does not show similar fracture pattern. It seems that in this specimen, multiple cracks may have initiated from multiple crack sites, including a larger spherical porosity (7000 μm) near the center, shortening its fatigue life.

Optical-stereo microphotographs of the fracture surfaces of D2P56 and D2P59 specimens are shown in Figure 4.8. They were fatigue tested at the total strain level of 0.3%. The fatigue life of D2P56 is 193 cycles and that of D2P59 is 460 cycles. Comparison of their

fracture surfaces shows significant differences in their pattern. The fracture surface of the bars D2P56 shows deeper crack valleys, which is not visible in D2P59. In these specimens, there is no visible large size porosity (1,000 μm) that was observed in D2P34 (Fig. 4.10). The porosity in D2P56 is of the order of 290 μm .

SEM microphotographs and particle volume fraction in neighboring fields for the D2P38 and D2P31 fatigue specimens are shown in Figures 4.25 and 4.27. There is uniform particle distribution in these two specimens except for SiC clusters in the interdendritic regions. The results of image analysis in Figures 4.28a and 4.28b show that the average particle volume fraction for D2P38 and D2P31 are 19.4 and 20 %, respectively. The D2P31 specimen has a more uniform particle distribution between fields than the specimen D2P38. The amount of porosity is 3% in D2P38 and 3.6% in D2P31. It is recognized that the most accurate method of determining the volume percentage of silicon carbide is the wet chemical analysis, which is discussed in another chapter of this report. This section attempts to relate properties to the two-dimensional microstructure as analyzed by image analysis.

Fig. 4.28a: Particle Distribution-D2P38

Fig. 4.28b: Particle Distribution-D2P31

In general, the propagation of cracks through the matrix also leads to the fracture of particles as seen in Figure 4.16. In addition, microstructural observations have shown that the inclusions and porosity are usually the sites for fatigue crack initiation in composite material. Figure 4.14 shows that fatigue cracks may have initiated from a pore near the surface and advanced into the matrix.

Fatigue cracks also form around inclusions as seen in Figures 4.16 and 4.25. This suggests that inclusions facilitate crack initiation and propagation. It is noted from these two figures that the size of fracture around the pore is more severe than in the matrix away from the pore. The presence of inclusions cause change in direction of crack propagation and causes more damage to the matrix around them. Figure 4.19 shows the presence of a large V shaped porosity associated with SiC particles in the matrix of the specimen D2P34 that has fatigue life of 7454 cycles, which is lower than that of the D2P24 (figure 4.20) specimen with fatigue life of 10,666 cycles at the total strain of 0.2%. It appears that porosity and inclusions significantly influence the fatigue life of

composite material. In an Al6061 alloy reinforced with Al_2O_3 particle, matrix damage was observed to be localized and occurred at large particles and particle clusters [19]. In this study, inclusion and porosity seems to have much stronger influence on the fatigue behavior than the particle distributions. The analysis, therefore, suggest that the enhancement of the fatigue behavior of cast MMCs require decrease in size of defect and amount of porosity and inclusions. In this study it was difficult to identify the fatigue crack initiation sites due to high SiC content of 20%. Sugimura and Suresh [13] also indicated that the striations could be seen in composites with 3% SiC but are not easily visible when SiC content is 20%.

4.5 Conclusions

Hysteresis loops obtained from strain controlled cyclic loading of 20% SiCp reinforced material did not exhibit any measurable softening or hardening.

1. Fatigue constants b , σ'_f , c , ϵ'_f , n' , and K' for Al-20% SiC composite were determined from the strain controlled fatigue test data. They can be used to predict fatigue life (Eqs. 4, 6, or 7) of a component made from this material and subjected to any random service loading.
2. The fatigue limit of the composite tested was calculated to be 100 MPa. It is higher than that of Duralcan A356-20% SiC cast alloy (60 MPa at 10^7 cycles). The A356-20%SiC alloy with the T6 heat treatment has longer fatigue life at higher stress magnitude compared to A356-20%SiC (Duralcan alloy).
3. The fatigue life of Al-20%SiC alloy with the T6 heat treatment showed wide variations between specimens at a given total strain, which appears to be related to factors such as inclusions and their volume fractions, porosity and particle distributions
4. Striations are generally not visible on the fracture surface of Al-20%SiC heat treated alloy tested in this study, but they can be seen on the fatigue fracture surfaces of the matrix alloy. It is reported in the literature [13] that the striations could be seen in composites with 3% SiC but are not easily visible when SiC content is 20%. Hence, this observation is not a surprise. In many specimens, SiC particle fracture was also observed. Fracture is more common around pores and inclusions than that in the matrix away from them. The inclusion and porosity seems to have much stronger influence on the fatigue behavior than the particle distributions. The analysis, therefore, suggest that to enhance the fatigue behavior of cast MMCs require decrease in size of defects and amount of porosity and inclusions.
5. The surfaces of the fatigue fractured samples show ductile dimples associated with α aluminum, cleavage fracture of Si phase and fractured SiC particles. Pullout SiC particles can also be observed.
6. In some fatigue samples, SiC particle fracture was also observed.

5A. Examination of Microstructure of Broken Al-SiC Bars Using Clemex Image Analysis System

Typical microstructures generated using the Image Analysis, Ultrasonic, and Chemical Analysis are reported in previous section of this report. The quantitative results with regard to volume percentage SiC, volume percent porosity and volume percent Si, and aspect ratios of Si and SiC are also given.

In the following section, some of the typical microphotographs of cast Al-SiCp composites generated during the year 2001 are shown. They show microstructural features, other than volume % SiC, which may influence the properties of the composites tested in this research.

- Large SiC particles surrounded by smaller silicon particles from the Al-Si eutectic, forming Si-SiC interfaces (Figure 5.1a-b). The interfaces between Si and SiC, relative to Al-Si and Al-SiC interfaces will influence the properties of these composites. This type of photomicrographs showing α Al-SiC, Si-SiC and Al-Si interfaces was submitted for a metallographic contest and the entry won the first prize in the Merryl Scheil Metallographic contest of ASM Milwaukee Chapter in May 2001.
- Angular porosity associated with SiC particles (Figure 5.1c and 5.1d): This type of porosity will reduce the strength and modulus of the composites. This type of porosity can come from clusters of silicon carbide, which had entrapped gas prior to their addition to the melt. The size, shape, and volume percent of this type of porosity and its degree of association with SiC particles will influence the mechanical properties of composites.
- Large spheroidal porosity in microstructure (Figure 5.1e): Relatively large porosity is observed frequently associated with SiC particles. These are probably gas bubbles in the melt with SiC particles preferentially migrating to the melt bubble interfaces. The volume percent and size of this type of porosity and the clustering of SiC particles around this type of porosity will influence the mechanical properties of the composites.
- Size and clustering of SiC particles (Figure 5.1f): These photomicrographs show areas of the microstructures relatively free from porosity. They show primary Al dendrites with SiC particles in the interdendrite regions. These microstructures show that some unusually large SiC particles are present in the microstructure. The photomicrographs also show that even in this relatively sound area of the microstructure, silicon carbide particles are frequently in contact with each other forming clusters in the interdendrite regions due to particle pushing. These clusters are different than the clusters present due to agglomeration of SiC particles prior to their addition to the melt and agglomeration in the melt during mixing. The degree of clustering due to particle pushing as observed in this type of microstructures will also influence mechanical properties of these composites.

It appears that in addition to size, volume % and aspect ratio of SiC and Si, there are a number of other microstructural features which may effect the properties of cast Al-SiC composites. It is felt that larger casting defects like porosity and inclusions (generally larger than $100\mu\text{m} \times 100\mu\text{m}$) have much greater effect on properties than microstructural features like vol% SiC, size of SiC, distribution of SiC, α dendrite spacing and silicon size. In fact, the relative importance of large casting defects vis a vis and smaller microstructural features must be studied in order to fully characterize behavior of these composites.

Fig. 5-1a: Al-SiC Sample showing large SiC particles surrounded by smaller Si particles

Fig. 5-1b: Al-SiC Sample showing large SiC particles surrounded by smaller Si particles, and other Si particles in contact with α aluminum

Fig. 5-1c: Al-SiC Sample showing non-spherical porosity associated with SiC particles

Fig. 5-1d: Al-SiC Sample showing large SiC particle associated with angular porosity

Fig. 5-1e: Large spheroidal porosity in Al-SiC sample associated with SiC particles

Fig. 5-1f: Microstructure of Al-SiC_p composite in an area relatively free from porosity, showing interdendritic clustering of large SiC particles

5B. Quantitative Results of some Microstructural Features determined by Image Analysis and their relation to Properties

Typical microphotographs of polished samples obtained from Image Analysis of 20 vol% SiC and 30 vol%SiC composites are shown in Figures 5.2 (a-d). The tensile strength and elastic modulus of the samples, when available, along with other features are also shown. They show α dendrites, SiC particles, silicon particles, and porosity. Table 5-1 lists the microstructural features of selected tensile specimens tested at Daimler-Chrysler during the year 2001, along with their tensile strength. It should be noted that the measured size of silicon carbide particles is much smaller than the nominal size specified by the manufactures of these materials. More extensive analysis of additional samples is needed to resolve these differences.

The preliminary correlations that can be established between measured strengths and microstructured features, based on a few samples, are outlined below

- For Al-20 vol % SiC composites, the tensile strength increases with vol % SiC until about 19.5 vol % SiC, and then decreases with further increase in vol % SiC. This may be due to the decreases in ductility above a certain volume percent SiC. However the effect of volume % SiC can be confounded with the effect of variation in porosity and other microstructured features.
- For Al-20 vol. % SiC composites, the tensile strength increases with density within the range (2.758 to 2.763 gm/cc) investigated.
- For Al-30 vol % SiC composites, the tensile strength decreases with increase in vol%SiC within the range observed.
- For Al-30 vol % SiC composites, the tensile strength decreases with an increase in density probably due to higher vol % SiC.
- For Al-20 vol % SiC sand cast bars the tensile strength of the bar with higher porosity, 5.74% by volume, is lower than the bar with lower porosity (1.16% by volume). However the effect of porosity can be confounded by the variation in volume % SiC and other microstructural features.

However it should be noted that the above trends are based on a very few samples and the trends will be on a more sound footing when data from larger number of bars are included in the analysis.

TABLE 5.1 PROPERTIES AND MICROSTRUCTURE OF SELECTED SAND-CAST AL-20%SiC BARS
TESTED AT
DAIMLER CHRYSLER IN 2001 AS DETERMINED BY IMAGE ANALYSIS

Sample No.	Tensile strength, MPa	Volume % SiC Average	Volume % Si Average	Aspect Ratio SiC Mean	Si Particle Size Average μm	SiC Particle Size μm	Si Aspect Ratio	Density g/cm^3	Porosity %
E4S10	282.5	24.1381	3.5410	1.5740	1.443	4.712	1.80085	2.808113	5.1573
E1S36 As Machined	291.8	27.4181	3.9097	1.5899	1.723	7.2085	1.67235	2.789621	2.7079
D2S46	324.4	21.4708	3.5197	1.6223	1.499	7.1045	1.6624	2.758151	5.7477
E4S34 As Cast	289.3	31.2124	1.9019	1.4988	1.538	7.895	1.7112	2.793347	3.1420
D2S32	338.5	19.1124	3.7242	1.6262	2.033	7.996	1.71905	2.762527	1.1624
D2S22	315.7	18.2671	4.4283	1.5582	1.508	7.930	1.6833	2.755319	1.8123
E4S36	244.1	26.5308	1.6714	1.5647	1.824	4.2895	1.68145		1.7203

Fig. 5.2 a: Microstructure of D2P31 sample, 200X, Volume % of SiC = 21 % (image analysis); % Porosity = 2.1402 (image analysis).

Fig. 5.2 b: Microstructure of D2P63 sample, 200X, Volume % of SiC = 17 % (image analysis); % Porosity = 5.7286 (image analysis).

Fig. 5.2 c: Microstructure of D2S22 sample, 200X, Volume % of SiC = 18 % (image analysis); % Porosity = 1.8123 (image analysis), Tensile Strength = 315.7 MPa

Fig. 5.2 d: Microstructure of D2S32 sample, 200X, Volume % of SiC = 19 % (image analysis); % Porosity = 1.1624 (image analysis), Tensile Strength = 338.5 MPa

Chapter 6. Wet Chemical Analysis

SiC volume fraction in composites can be determined using image analysis, wet chemical analysis, and ultrasonic velocity. SiC volume fraction determined by the three different methods were compared to identify more reliable method for correlating SiC volume fraction and strength. In recent times a consensus is building that the most reliable method for determining volume percentage SiC is the wet chemical analysis method. Figure 6.1 shows the location in broken tensile bars where the samples for wet chemical analysis were taken from cast Al-SiC composite tensile bars. Samples for wet chemical analysis were sent to Oshkosh Truck for the analysis. Selected results received from Oshkosh are shown in Table 6.1 along with SiC vol.% determined by ultrasonic method and the tensile strength of Al-20 and 30% SiC composites.

sample from test section

FIGURE 6.1 SAMPLE TAKEN FROM BROKEN TENSILE BARS FOR MICROSCOPIC EXAMINATION AND DETERMINATION OF VOLUME % SiC.

Table 6.1. Results of SiC volume fraction determined by ultrasonic velocity and wet chemical analysis in Al356/20 and 30 % SiC.

Nominal SiC vol.%	Calculated SiC vol. % using ultrasonic method	Wet chemical analysis results vol. % SiC	Tensile strength, ksi
20	18.86	18.3927	
20	19.45	19.2638	
20	14.57	18.8436	49.730
20	15.04	19.4646	53.083
20	18.38	20.4767	49.528
20	21.43	19.5617	48.676

20	16.13	20.8396	46.263
30	29.88	28.4313	42.710
30	17.37	29.0388	41.051
30	22.86	28.5939	46.630
30	28.19	28.9847	41.491
30	28.07	29.1699	45.831
30	27.51	30.5890	35.687
30	28.08	29.2389	49.881
30	26.53	30.5563	46.491
30	28.90	29.5112	47.270
30	29.98	29.3521	52.730

Figures 6.2 and 6.3 were plotted based on the data shown in Table 6.1 to identify the variation in SiC volume percentage determined by ultrasonic velocity and wet chemical analysis in the samples containing SiC of 20 and 30 nominal volume fractions, respectively. It can be noted that the variation in SiC vol.% measured by wet chemical analysis is less than that in SiC volume fraction measured by ultrasonic velocity. The average volume fractions of SiC determined by (a) ultrasonic method and (b) wet chemical analysis, in the samples with 20 nominal volume fraction of SiC, are 17.69 and 22.80%, respectively. For the composite test bars containing 30 nominal volume percentage SiC, the average volume fraction determined by ultrasonic velocity is 26.67%; however, the average volume percentage determined by wet chemical analysis is 29.35%. This indicates that wet chemical analysis method leads to vol.% SiC values which deviate much less from the nominal volume fraction than the ultrasonic velocity measurements. In general the wet chemical analysis gives values of SiC vol.% which are higher than the values of SiC% obtained by ultrasonic measurement; the differences in vol.% SiC obtained by the two methods vary from samples to sample and can be as large as up to 5 vol.%. In view of ALCAN'S recommendation one must use wet chemical analysis for determining the volume percent SiC.

Figure 6.2. Differences between SiC volume fractions determined (a) using (a) wet chemical analysis and (b) ultrasonic method in the samples with 20% (nominal volume fraction) SiC.

Figure 6.3. Differences between SiC volume fractions determined (a) using (a) wet chemical analysis and (b) ultrasonic method in the samples with 30% (nominal volume fraction) SiC.

To identify any relationship between SiC vol.% measured by wet chemical analysis and tensile strengths of individual bars, the tensile strengths of the composites with 20 % (nominal vol.%) and 30% SiC are plotted in Figures 6.4 and 6.5, as a function of particle volume fraction determined by wet chemical analysis, respectively. There does not seem to be a clear correlation between the measured tensile strength and the volume percent SiC measured using the wet chemical analysis method, specially in the case of Al-30 vol. % SiC alloys. Apparently the casting defects have a more pronounced effect on the tensile properties of individual bars cast in this study, as compared to the effect of volume percent SiC.

Figure 6.4. Variation in the tensile strength of Al-20% (nominal %) SiC with SiCp volume fraction as determined using wet chemical analysis.

Figure 6.5. Variation in the tensile strength of Al-30% (nominal %) SiC with SiCp volume fraction as determined using wet chemical analysis.

The results of vol. % SiC measured using Clemex image analysis system and wet chemical analysis are compared along with the tensile strength of different Al-SiC composite test bars as shown in Figure 6.6. For 20 nominal vol.% SiC the wet chemical analysis gives a value of % SiC which is slightly higher than the value given by Clemex image analysis. The value given by wet chemical analysis is closer to the nominal value. For 30 nominal vol.% SiC, the values determined by wet chemical analysis are slightly lower than the values determined by Clemex image analysis; the values determined by Clemex image analysis are much closer to the nominal value. The tensile bar showing a higher tensile strength had lower vol.% SiC, specially when determined by wet chemical analysis. This again suggests that casting defects have a more pronounced effect on tensile properties of individual bars as compared to volume percent SiC.

(a) 20 nominal SiC vol.%

(b) 30 nominal SiC vol.%

Figure 6.6 SiC particle volume fractions for a given tensile strength of Al-SiC composite tensile bars.

7. Publications and Presentations Based on the Project Work

a. A paper based on this work was already published in AFS Transactions in 2000 with the title "Correlation Between Structure and Mechanical Properties of Cast SiC particulate Reinforced Al-Alloy Matrix Composites"; this paper is attached as an Appendix I. The two research papers based on this work and submitted to AFS Transactions in 2002 are attached as appendices II and III to this report. The changes as suggested by the AFS reviewers have been incorporated in the papers. Another paper based on this work was presented before the Indianapolis Conference of ASM/TMS in 2001 and published in the proceedings. A copy of this paper is attached to this report as appendix IV.

b. In April 2001 a metallographic poster entitled "Solid-Solid Interfaces in Cast Al-Si-SiC_p Composites" based on the project received the first prize in Merryl Schiel Metallographic Contest of the American Society of Metals (ASM), Milwaukee Chapter. In April 2002 another poster based in the project work received the third prize in Metallurgical contest of ASM Milwaukee Chapter.

8. Conclusions

1. The moduli of the composites containing 20 and 30% SiC cast in permanent molds are, in general, higher than those cast in sand molds. However, in some cases, the reverse trend was observed.
2. The dependence of tensile strength of the composite with 20% SiC and 30% SiC on density and porosity was identified. The result shows that in general the higher tensile strength is associated with lower porosity and higher density. However, a few samples exhibited the trend contrary to this observation.
3. The Al-20% SiC samples having more inclusions exhibited a lower tensile strength than the samples with fewer inclusions. It appears that cracks leading to the tensile fracture frequently start from inclusions. This suggests that macroscopic casting defects such as micro-porosity, shrinkage porosity and inclusions appear to influence the tensile strength more than the microstructure and particle distribution. There was no significant difference in the types of the defects between the specimens with high tensile strength and low tensile strength.
4. The foundry casting the tensile test specimens had a very significant influence on the tensile properties. The tensile strength and modulus cast at one foundry were found to be higher than the specimens cast at another foundry. The testing laboratories seem to also have a significant effect on mechanical properties.
5. The composites with 30% SiC (Duralcan F3S.30S, and Lanxide 4040-30P) showed higher modulus than those containing 20% SiC (Duralcan F3S.20S) as expected. However, the tensile strength of Duralcan F3S.30S containing 30% SiC was found to be lower than the Duralcan F3S.20S containing 20% SiC. It is felt that this may be due to the particle size used in making these materials (30% SiC material was made using 20-25 μm particle while 20% SiC material was made using 10-12 μm particle). The tensile strength of Lanxide 4040-30P was higher than the Duralcan F3S.30S and was close to that of Duralcan F3S.20S.
6. The fatigue limit of A359-20%SiC composite tested was measured to be 100 MPa with longer fatigue life which is higher than that of Duralcan A356-20%SiC cast alloy (60 MPa at 10^7 cycles).
7. The fatigue life of Al-20%SiC alloy with the T6 heat treatment showed wide variations between specimens at a given total strain, which appears to be related to factors such as inclusions and their volume fractions, porosity and particle distributions
8. Striations are generally not visible on the fracture surface of Al-20%SiC heat treated alloy tested in this study, but they can be seen on the fatigue fracture surface of the matrix alloy. In many specimens, SiC particle fracture was also observed. Fracture is more common around pores and inclusions than that in the matrix away from them. The inclusion and porosity seem to have a much stronger influence on the fatigue behavior than the particle distribution. The analysis therefore suggests that the decrease in the size of defects, amount of porosity and inclusions help in enhancing the fatigue behavior of cast MMCs.

9. The surfaces of the fatigue fractured samples show ductile dimples associated with α aluminum, cleavage fracture of Si phase and fractured SiC particles. Pullout SiC particles can also be observed.

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Appendix I

Paper entitled “Correlation Between Structure and Mechanical Properties of Cast SiC particulate Reinforced Al-Alloy Matrix Composites” published in AFS Transaction in 2000

CORRELATION BETWEEN STRUCTURE AND MECHANICAL PROPERTIES OF CAST SiC PARTICULATE REINFORCED Al-ALLOY MATRIX COMPOSITES

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ABSTRACT

Ingots of 20% and 30% silicon carbide particle reinforced aluminum based alloy composites from two different suppliers, were remelted, cast into tensile bars by three foundries using the permanent mold and the sand mold processes. All the samples were T6 heat-treated. The mechanical properties of the composites were measured by the three independent test laboratories (X, Y and Z). The analysis showed that alloy producer, foundry, test lab, type of mold and SiC particle loading have measurable influence on the mechanical properties of the composites. However, no significant differences were observed between the mechanical properties of machined and unmachined tensile bars. The mechanical properties measured by one of the testing laboratories Y are higher than those measured by either of the two other testing laboratories (X and Z). The percent elongations reported by one of the laboratories (Z) are much higher (2-3 times) than those reported by the two other (X and Y). The range of tensile property data generated in this study are comparable to the property data published by other researchers. The macro structure and microstructure of the fracture surface of the tensile test bars were also investigated using stereo optical microscope and SEM-EDX. The main factors, which appear to be associated with lower tensile properties in certain bars of the same compositions, were casting defects including shrinkage, gas porosity, oxide inclusions and cracks. The modulus of Al-30% SiC tensile bars was more than the modulus of Al-20% SiC bars. However the tensile strength and elongations of Al-30% SiC were lower than the tensile strength and elongations of Al-20% SiC bars. The results obtained further underline the need for standardization in foundry practice and testing of Al-SiC composites.

Appendix II

Paper entitled “Fatigue Behavior of Permanent Mold Cast A356-20% SiC Composite” submitted to AFS for Publication in 2003 Transactions and Presentation at AFS National Conference

FATIGUE BEHAVIOR OF PERMANENT MOLD CAST A356-20% SiC_p COMPOSITE

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ABSTRACT

The current investigation is undertaken to study the strain controlled fatigue behavior of permanent mold cast specimens of A356-20% SiC_p composite heat-treated to T6 Condition. The investigation involves identifying the specimens with low and high fatigue lives at a given total strain level and determining the cause of this behavior. The fatigue samples were cast in one foundry and were tested in one laboratory.

Quantitative image analysis, optical stereo microscopy and scanning electron microscopy were used to study the microstructure and the fracture surface and to identify cause of the high and low fatigue life. The fatigue life of Al-20% SiC heat treated alloy at a given total strain showed wide variation in fatigue life, which appears to be related to factors such as inclusions and their volume fractions, porosity, and particle distributions. The inclusions and porosity on the fracture surfaces seem to have a more significant influence on the fatigue life of cast Al-20% SiC, as compared to other variables, including SiC particle volume percentage and its distribution.

Appendix III

Paper entitled “Scatter in Tensile Properties of Cast A359-SiC aluminum alloys” submitted to AFS for Publication and Presentation in 2003 Transactions at AFS National Conference

SCATTER IN TENSILE PROPERTIES OF CAST A359-SiCp ALUMINUM ALLOYS

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ABSTRACT

The current investigation was undertaken to identify the influences of foundry, alloy supplier, testing laboratory and volume % SiCp on the mechanical properties of cast SiCp reinforced Al-matrix composites, which may help in determining the reproducibility in the properties in a given composite. The tensile specimens were cast from three different MMC materials received from two suppliers. They were cast to the shape defined by ASTM E505 at three independent foundries but heat-treated to T6 condition at one source. The tensile tests were performed at three different industrial laboratories. A few of these specimens were machined to determine the effect of surface finish.

Initial analysis of effects of variables was done using average values, which was followed by a limited statistical analysis to determine the scatter in tensile properties. The foundry casting the tensile bars and the testing laboratories were found to influence the mechanical properties. The modulus of the composites with 30% SiC was observed to be higher than that of the composites with 20% SiC. However, the tensile strength of the composite containing 30% SiC was found to be lower than that containing 20% SiC. Statistical analysis was performed on the tensile test data using commercially available software SYSTAT. The analysis was performed to determine scatter in tensile properties due to (1) testing laboratory, (2) casting foundry, (3) material suppliers, (4) machining and non-machining (surface finish), and (5) mold type (sand or permanent). The analysis was made to determine percent contribution of each of the above factors on the tensile strength. The effect of %SiC_p on tensile properties was also analyzed.

Appendix IV

Paper entitled “Tensile and Fatigue Properties of Permanent mold Cast A359-SiCp Aluminum Alloys”, published in TMS Annual Meeting in Indianapolis, 2001.

TENSILE AND FATIGUE PROPERTIES OF PERMANENT MOLD CAST A359-SiCp ALUMINUM ALLOYS

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Abstract

The current investigation was undertaken to study the influence of foundry, alloy supplier, testing laboratory and % SiCp on mechanical properties of SiCp reinforced Al-matrix composites. Ingots of 20% and 30% SiCp reinforced aluminum based alloy composites were re-melted and permanent mold cast into tensile bars at three different foundries. All the bars were heat treated to T6 at one location. Their properties were measured at three different laboratories X, Y and Z. The intent of using three different foundries and three independent test laboratories was to determine the reproducibility in the properties in a given composite. The variability in the data was determined to develop standard handbook grade data to facilitate design using these materials. Cast tensile bars from one foundry were also machined to smaller size fatigue bars and fatigue tested under strain-controlled mode to study the cyclic behavior of the composite and to determine its fatigue properties.

Increase in SiC content from 20% to 30% showed small decrease in average tensile strength. However, the decrease was within ± 1 standard deviation. The Duralcan 20% SiC material, showed no measurable cyclic softening or hardening under fatigue loading. The coefficients of fatigue life equation have been determined from the data and the equation for total strain as a function of fatigue life has been determined

Appendix V

Results of Wet Chemical Analysis for Volume Percent SiC in
Broken Tensile Bars from Oshkosh Truck

Control Verification Data for Gravimetric Determination of SiC					
Date	Batch I.D.s	Residue wt.	Sample wt.	Weight% of SiC	Volume% of SiC
03/14/2002	2CS 6 - C2P 5	0.0566	0.2541	22.2747	19.3070
04/19/2002	2CS 6, C2P 8 - C2P 31	0.0588	0.2571	22.8705	19.8437
04/25/2002	C2P 32 - C3P 7	0.0594	0.2607	22.7848	19.7664
05/02/2002	C2P 59, C3P 5, C3P 10 - C3P25	0.0544	0.2546	21.3668	18.4913
05/10/2002	C3P 36 - C3S17	0.0619	0.2598	23.8260	20.7067
05/15/2002	C2P 59, C39 5, 10, 20, 25, 58, C3S 19	0.0621	0.2683	23.1457	20.0920
05/16/2002	C3S 20 - C3S 48	0.0602	0.2607	23.0917	20.0432
05/22/2002	C3S 50 - D2P 9	0.0555	0.2444	22.7087	19.6978
				Average:	19.744
				Standard Deviation:	0.645

According to Alcan, the control sample contains 20 volume% SiC +/- 2%

The gravimetric determination of vol% SiC for Aluminum Metal Matrix Composites					
Sample I.D. *	Scribed Tensile Bar I.D. **	Residue wt.	Sample wt.	Weight% of SiC	Volume% of SiC
control (Alcan)		0.0566	0.2541	22.2747	19.3070
2CS 6	G2C 56	0.0480	0.2539	18.9051	16.2922
2CS 52	C2S 52	0.0558	0.2568	21.7290	18.8164
C2P 5	2CP 5	0.0531	0.2430	21.8519	18.9268
C2P 8	C2P 8	0.0534	0.2512	21.2580	18.3937
C2P 11	C-2CP 11	0.0504	0.2545	19.8035	17.0927
C2P 19	C2P 19	0.0580	0.2613	22.1967	19.2368
C2P 21	C1CP 21	0.0582	0.2664	21.8468	18.9223
C2P 22	C-2CP 22	0.0591	0.2581	22.8981	19.8686
C2P 31	C2P 31	0.0610	0.2642	23.0886	20.0404
C2P 32	2PC 32	0.0614	0.2638	23.2752	20.2089
C2P 37	2PC 37	0.0564	0.2592	21.7593	18.8436
C2P 40	C-2CP 40	0.0605	0.2605	23.2246	20.1632
C2P 41	C2P 41	0.0577	0.2472	23.3414	20.2687
C2P 43	2PC 43	0.0592	0.2637	22.4498	19.4646
C2P 52	2CP 52	0.0582	0.2571	22.6371	19.6333
C2P 54	2CP 54	0.0600	0.2719	22.0669	19.1201
C2P 59	2CP 59	0.0600	0.2704	22.1893	19.2302
C3P 4	C3P 4	0.0834	0.2540	32.8346	28.9847
C3P 5	3PC 5	0.0880	0.2664	33.0330	29.1699
C3P 6	3CP 6	0.0802	0.2492	32.1830	28.3772
C3P 7	C-3CP 7	0.0822	0.2499	32.8932	29.0393
C3P 10	3CP 10	0.0797	0.2449	32.5439	28.7135
C3P 13	3CP 13	0.0801	0.2513	31.8743	28.0898
C3P 15	C-3CP 15	0.0864	0.2620	32.9771	29.1177
C3P 20	3CP 20	0.0876	0.2454	35.6968	31.6695
C3P 25	C3P 25	0.0731	0.2220	32.9279	29.0718
C3P 36	C3P 36	0.0872	0.2524	34.5483	30.5890
C3P 56	C3P 56	0.0877	0.2649	33.1068	29.2389
C3P 57	C-3CP 57	0.0890	0.2661	33.4461	29.5560
C3P 58	3CP 58	0.0868	0.2522	34.4171	30.4658
C3P 60	C-3CP 60	0.0843	0.2591	32.5357	28.7058
C3S 7	C3S 7	0.0807	0.2511	32.1386	28.3358
C3S 17	3CS 17	0.0950	0.2739	34.6842	30.7166
C3S 19	C-3CS 19	0.0882	0.2626	33.5872	29.6880
C3S 20	3CS 20	0.0797	0.2472	32.2411	28.4313
C3S 26	3CS 26	0.0825	0.2548	32.3783	28.5591
C3S 27	3CS 27	0.0821	0.2496	32.8926	29.0388
C3S 28	C-3CS 28	0.0817	0.2519	32.4335	28.6106
C3S 37	C3S 37	0.0793	0.2440	32.5000	28.6725
C3S 38	3SC 38	0.0808	0.2540	31.8110	28.0310

C3S 40	3CS 40	0.0791	0.2514	31.4638	27.7083
C3S 42	C3S 42	0.0789	0.2512	31.4092	27.6576
C3S 43	C-3S 43	0.0798	0.2533	31.5041	27.7458
C3S 44	3CS 44	0.0848	0.2594	32.6908	28.8505
C3S 48	C3S 48	0.0875	0.2754	31.7720	27.9947
C3S 50	3CS 50	0.0836	0.2579	32.4157	28.5939
C3S 51	C-3CS 51	0.0811	0.2549	31.8164	28.0360
D1S 23	GLDS 23	0.0783	0.2610	30.0000	26.3520
D1S 25	1DS 25	0.0769	0.2532	30.3712	26.6953
D1S 27	G1SD 27	0.0766	0.2530	30.2767	26.6078
D1S 30	D1S 30	0.0780	0.2711	28.7717	25.2192
D1S 37	D1S 37	0.0754	0.2510	30.0398	26.3888
D1S 47	G1DS 47	0.0747	0.2440	30.6148	26.9208
D2P 5	2PD 5	0.0623	0.2643	23.5717	20.4767
D2P 8	C-2DP 8	0.0577	0.2412	23.9221	20.7936
D2P 9	D2P 9	0.0624	0.2727	22.8823	19.8543
D2P 13	D2P 13			N/A	N/A
D2P 16	D2P 16			N/A	N/A
D2P 18	2PD 18			N/A	N/A
D2P 21	C-2DP 21			N/A	N/A
D2P 35	2PD 35			N/A	N/A
D2P 39	D2P 39			N/A	N/A
D2P 44	D2P 44			N/A	N/A
D2P 55	D2P 55			N/A	N/A
D2S 51	G2DS 51			N/A	N/A
D2S 54	D2S 54			N/A	N/A
D2S 57	2DS 57			N/A	N/A
E1P 1	IPE 1			N/A	N/A
E1P 5	1EP 5 or 1EP 56			N/A	N/A
E1P 6	C1EP 6			N/A	N/A
E1P 10	C-1EP 10			N/A	N/A
E1P 21	9-1EP-21			N/A	N/A
E1P 29	E1P 29			N/A	N/A
E1P 32	IEP 32			N/A	N/A
E1P 35	C1EP 35			N/A	N/A
E1P 39	1EP 39			N/A	N/A
E1P 50	1EP 50			N/A	N/A
E1P 55	E1P 55			N/A	N/A
E1S 9	1ES 9			N/A	N/A
E1S 15	E1S 15			N/A	N/A
E1S 22	1ES 22			N/A	N/A
E1S 24	E1S 24			N/A	N/A
E1S 27	E1S27			N/A	N/A
E1S 39	E1S 39			N/A	N/A
E4P 23	E4P 23			N/A	N/A
E4P 51	G 4EP 51			N/A	N/A

E4S 3	4ES 3			N/A	N/A
E4S 9	4ES 9			N/A	N/A
E4S 11	E4S 11			N/A	N/A
E4S 14	E4S 14			N/A	N/A
E4S 19	E4S 19			N/A	N/A
E4S 32	E4S 32			N/A	N/A
E4S 38	E4S 38			N/A	N/A
E4S 40	E4S 40			N/A	N/A
E4S 46	4ES 46			N/A	N/A
E4S 57	E4S 57			N/A	N/A