Fracture Toughness of Discontinuous SiC Reinforced Aluminum Alloys

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ABSTRACT

A review is provided of the fracture toughness characterizations that have been published on discontinuous SiC reinforced aluminum alloys. Surprisingly few investigations have been conducted on these materials, particularly when viewed in the context of the significance of this property for widescale application of these materials. It was also found that the majority of the available data failed to conform to ASTM E 399 plane strain fracture toughness criteria, creating considerable difficulty in properly assessing the meaningfulness of the data. A thorough tabulation of the data is provided, along with a critique of the experiments and the data. The major factors which affect fracture resistance in these materials are also discussed. These factors include: material thickness, SiC reinforcement effects, aluminum alloy chemistry, mechanical working and secondary processing, and powder metallurgy vs. ingot metallurgy.

KEYWORDS

Fracture toughness; discontinuous reinforced aluminum alloys.

INTRODUCTION

Discontinuous SiC reinforced aluminum alloys offer great potential for many demanding structural applications because of their high specific strength and stiffness properties. These materials are made by both powder metallurgy (PM) and ingot metallurgy (IM) processes, employing either whisker (w) or particulate (p) SiC reinforcements typically ranging in size from 0.5 μm to 20 μm. In spite of the promise these materials exhibit, a major drawback to their widespread use has been the poor fracture toughness these materials have displayed. Despite this major restriction, it is surprising how little concentrated effort has been given to improving the fracture resistance of these systems. This paper seeks to review the documented properties of these MMC in the open literature and comment on the directions that are being pursued for improving toughness.

FRACTURE TOUGHNESS EVALUATIONS OF DISCONTINUOUS SiC REINFORCED ALUMINUMS

A summary of research investigations detailing fracture toughness measurements on discontinuous SiC reinforced aluminums is given in Table 1. (See Table 1 for reference citations.) These references [1-21] provide fracture toughness values of a wide variety of these composites, including both PM and IM process metal matrix composite (MMC) formulations. Table 1 provides information that is critical to evaluating toughness values of the materials: the base alloy, the reinforcement volume fraction and type, the material form, and the approximate date when manufactured. The last item is essential for understanding the data's relevance to current improved technology for producing these MMC's. It is also noteworthy that so few references can be cited in the open literature regarding fracture toughness evaluations and that very few research groups have been active in this area. It might be presumed that considerably greater information is available in U.S. aerospace industry contract reports that have yet to be published widely; however, this is not the case, with only four major efforts being directed at this subject (Bates; Carroll; Chellman, 1985; Steelman et al., 1987) beyond those being pursued by the materials suppliers themselves.

TABLE 1. RESEARCH INVESTIGATIONS OF THE FRACTURE TOUGHNESS OF DISCONTINUOUS SiC REINFORCED ALUMINUM ALLOYS

Alloy Matrix	Reinforcement		Material Form	Approximate Manufacture Date	Reference
	%	Type			
2014	15 & 25	Particulate	Cast/Extruded	1986	[1] - Davidson
2024	15	Particulate	Cast/Extruded	1986	[1] - Davidson
2024	15	Particulate	Extruded	1980	[2] - Divecha, et al.
2124	13	Whisker	Extruded	1986	[3] - Marchand, et al.
2124	15	Whisker	Rolled	1986	[4] - Cook & Mohn
2124	15	Whisker	Rolled	1986	[5] - Mohn & Vukobratovich
2124	15	Whisker	Rolled	1987	[6] - ACMC data
2124	20	Whisker	Extruded	1985	[7] - Goolsby & Petty-Galis
2124	20	Particulate	Extruded	1986	[8] - Harrigan
2124	20	Particulate	Rolled	1986	[8] - Harrigan
2124	25	Particulate	Rolled	1985	[8] - Harrigan
5456	15	Particulate	Extruded	1980	[2] - Divecha, et al.
6061	15	Particulate	Extruded	1980	[2] - Divecha, et al.
6061	20	Particulate	Rolled	1982	[9] - Goolsby
6061	20	Whisker	Extruded	1984	[10] - Hasson, et al.
6061	20	Whisker	Extruded/Rolled	1984	[11] - Crowe, et al.
6061	20	Whisker	Extruded	1984	[12] - Goolsby
6061	25	Particulate	Rolled	1984	[12] - Goolsby
6061	25	Particulate	Rolled	1984	[11] - Crowe, et al.
6061	30	Particulate	Rolled	1985	[13] - Tsangarakis, et al.
7075	30	Particulate	Rolled	1985	[13] - Tsangarakis, et al.
7090	25	Whisker	Rolled	1983	[14] - Goolsby & Austin
7091	30	Particulate	Extruded/ Rolled	1985	[15,16] - Austin & Goolsby
MB78	20	Particulate	Extruded	1987	[17] - Shang, et al.
MB85	15 & 20	Particulate	Extruded	1987	[18] - Gurganis
7475	15	Particulate	Cast/Extruded	1986	[1] - Davidson
IN-9021	14	Particulate	Extruded	1985	[1] - Davidson
IN-9052	15	Particulate	Extruded	1985	[1,19] - Davidson
Al-4 Mg	15	Particulate	Cast/Extruded	1986	[1] - Davidson
A356	30	Particulate	Cast/Hipped	1987	[20] -Stephens, et al.
A357	10 & 20	Particulate	Cast/Hipped	1987	[21] - Austin & Saathoff
A357	30	Particulate	Cast/Hipped	1987	[20] -Stephens, et al.

Specific data reported by the references enumerated in Table 1 are given in Tables 2 through 5. These tables have been organized to show data for 2XXX based PM materials, 6061 based PM materials, other PM materials, and cast materials. Almost all of these data fail to meet ASTM E 399 criteria for plane strain fracture toughness, so these data are simply listed as critical stress intensity factor (K_c) values. This is consistent with the nomenclature that many of the referenced authors chose to use, especially for investigations where thin sections were tested. This K_c value was routinely determined using the maximum load observed during test and not with a P_Q load determined via ASTM's 95% secant method. More appropriately, these K_c values should be reported as apparent fracture toughness K_{app}, following the procedure recommended in the Damage Tolerant Design Handbook.

Two columns provided in Tables 2 through 5 have been included for more meaningful interpretation of the data: (1) a column reporting the ratio $B/(K_c/s_y)^2$ and (2) a comments column. (B is defined as specimen thickness and s_y as material yield strength.) The $B/(K_c/s_y)^2$ ratio is crucial for deciding whether the data reported can be considered plane strain. For metals, a ratio value greater than 2.5 is considered a conservative indication of plane strain behavior. For this type of MMC material, no guidelines have been developed to differentiate plane strain data from K_c values that would be geometry dependent. Data reported in this paper will be discussed subsequently in this regard. With respect to the comments column of Tables 2 through 5, key factors are noted which need to be considered in interpreting the reported fracture toughness values. Data will probably be anomously high for those investigations employing: subsize specimens [2,3] (Divecha et al., 1981; Marchand et al., 1988); failure conditions observed in fatigue crack growth tests [1,19], (Davidson, 1987); no fatigue precrack [10] (Hasson et al.,1985); or short rod tests [2,8,20] (Divecha et al., 1981; Harrigan; Stephens et al., 1988).

CRITIQUE OF TEST PROCEDURES AND DATA

The tabulations of Tables 2 through 5 point out the extreme lack of valid K_{Ic} data that have been generated on these materials, if ASTM E399 criteria are assumed applicable. This has been due primarily to: (1) the limited amounts of material available for characterization in most studies, (2) the limited forms of available material, (3) the initially high cost of these materials, and (4) the difficulties encountered in successfully fatigue precracking many of these materials. With the improved material availability and lower material costs that now exist for these materials, investigators must be much more diligent in properly testing and fully reporting fracture toughness values and procedures. Until the MMC community sees fit to validate other criteria, ASTM E399's criteria should be used for evaluation. At present there is no evidence that these criteria are not appropriate for discontinuous SiC reinforced aluminums.

It should be noted that irregardless of test procedures, the fracture toughness values of these MMC materials are typically considered to be no better than one-half to two-thirds of those values for the unreinforced aluminum alloys from which they are composed. For example for the 2124 alloy (considered to be the toughest matrix for these MMC), the unreinforced alloy at 10.2 mm thickness and yield strength of 380 MPa has a plane strain fracture toughness of 75.8 $MPa \cdot m^{1/2}$ in the LT orientation (Damage Tolerant Design Handbook). From Table 2 the comparable MMC material closest in thickness (6.35 mm) for achieving plane strain has a fracture toughness K_c of 44 $MPa \cdot m^{1/2}$ [6] (Advanced Composite Materials Corp.,1988). It should be pointed out that this

TABLE 2. FRACTURE TOUGHNESS CHARACTERIZATIONS OF DISCONTINUOUS SiC REINFORCED 2XXX PM ALUMINUM ALLOYS.

Alloy Matrix	Reinforcement		Material Form	Orientation	Specimen Thickness B (mm)	Yield Strength S_y (MPa)	Fracture Toughness K_c (MPa $\sqrt{m}$)	B/ $(K_c/S_y)^2$	Ref. No.	Comments
	%	Type								
2024	15	P	Extruded	L-T	2.70*	-	14.0	-	[2]	Short rod test; no fatigue precrack; data reported as K_{Ic}.
2124	13	W	Extruded	L	8.00*	500	21.0	4.54*	[3]	K_c calculated from J_{Ic} measurement on 8 mm round specimen
2124	15	W	Rolled	L-T T-L	2.54 2.54	573 386	55.0 59.0	0.28 0.11	[4]	No description of test procedure.
2124	15	W	Rolled	L-T T-L	2.54 2.54	573 386	59.0 64.0	0.24 0.09	[5]	No description of procedure; material apparently same as [4].
2124	15	W	Rolled	L-T L-T L-T	1.78 3.18 6.35	557 557 557	59.0 47.0 44.0	0.16 0.45 1.02	[6]	No description of test procedure.
2124	20	W	Extruded	L-T T-L	3.18 3.18	419 380	26.5 15.4	0.79 1.94	[7]	Failed ASTM E399 thickness criterion; K_{app} = 29.0 (L-T) & 20.8 (T-L).
2124	20	P	Extruded	L-T	12.70	414	25.9	3.24	[8]	Short rod test; no fatigue precrack; data reported as K_{Ic}.
2124	20	P	Rolled	L-T	2.18	352	66.0	0.06	[8]	Failed ASTM E399 thickness criterion; data reported as mixed mode failure (plane stress/plane strain).
2124	25	P	Rolled	L-T	2.54	396	51.7	0.15	[8]	Failed ASTM E399 thickness criterion; data reported as mixed mode failure (plane stress/plane strain).

* Round specimen of specified diameter tested.

TABLE 3. FRACTURE TOUGHNESS CHARACTERIZATIONS OF DISCONTINUOUS SiC REINFORCED 6061 PM ALUMINUMALLOY

Alloy Matrix	Reinforcement		Material Form	Orientation	Specimen Thickness (mm)	Yield Strength S_y (MPa)	Fracture Toughness K_c (MPa $\sqrt{m}$)	B/ $(K_c/S_y)^2$	Ref. No.	Comments
	%	Type								
6061	15	P	Extruded	L-T	2.70*	-	31.7	-	[2]	Short rod test; no fatigue precrack; data reported as K_{Ic}.
6061	20	P	Rolled	L-T	2.29	345	30.1	0.30	[9]	Failed ASTM E399 thickness, max load to conditional load ratio criteria.
6061	20	W	Extruded	L-C L-C L-C L-C R-L C-L	12.70 12.70 12.70 12.70 12.70 12.70	335 375 175 374 374 374	19.5 23.4 18.9 22.4 14.0 17.6	3.75 3.26 1.09 3.54 9.06 5.73	[10]	Specimens were not fatigue precracked; data reported as K_{Ic}.
6061	20	W	Extruded Rolled Rolled	L-C L-T T-L	12.70 6.35 6.35	374 443 409	22.4 7.1 6.3	3.54 24.72 26.76	[11]	Extruded L-C specimens were not fatigue precracked; data reported as K_{Ic}.
6061	20	W	Extruded	L-T T-L L-T T-L	5.08 5.08 12.70 12.70	392 313 392 313	14.7 10.2 8.8 9.0	3.61 4.78 25.20 15.36	[12]	Failed ASTM E399 max allowable fatigue load, max load to conditional load ratio criteria; K_{app} for 5.08 mm tests were 15.8 (L-T) and 13.1 (T-L). K_c values for 12.7 mm tests determined from failure during precracking.
6061	25	P	Rolled	L-T T-L	4.06 4.06	375 375	15.6 15.2	2.35 2.47	[12]	Failed ASTM E399 max load to conditional load ratio criterion; K_{app} values for these tests were 18.3 (L-T) and 16.6 (T-L).
6061	25	P	Rolled	L-T T-L	6.35 6.35	345 350	15.8 14.5	3.03 3.70	[11]	
6061	30	P	Rolled	L-T T-L L-T T-L	1.60 1.60 11.70 11.70	440 440 440 440	31.0 27.0 15.5 15.5	0.32 0.42 9.43 9.43	[13]	Specimens may not have been precracked; data assumed to be for 6061 Al matrix (could be for 7075 Al matrix).

* Round specimen of specified diameter tested.

TABLE 4. FRACTURE TOUGHNESS CHARACTERIZATIONS OF VARIOUS DISCONTINUOUS SiC REINFORCEDPM ALUMINUM ALLOYS

Alloy Matrix	Reinforcement		Material Form	Orientation	Specimen Thickness (mm)	Yield Strength S_y (MPa)	Fracture Toughness K_c (MPa $\sqrt{m}$)	B/ $(K_c/S_y)^2$	Ref. No.	Comments
	%	Type								
5456	15	P	Extruded	L-T	2.70*	-	17.0	-	[2]	Short rod tests; no fatigue precrack; data reported as K_{Ic}.
7075	30	P	Rolled	L-T T-L	1.60 1.60	613 613	21.0 21.0	1.36 1.36	[13]	Specimens may not have been fatigue precracked;data assumed to be for 7075 Al matrix (could be for 6061 Al matrix).
7090	25	W	Rolled	L-T L-T	2.16 7.62	584 587	8.4 7.9	10.44 42.07	[14]	Failed ASTM E399 max allowable fatigue precracking load criterion.
7091	30	P	Extruded Extruded Extruded/Rolled Extruded/Rolled	L-T L-T L-T L-T	4.57 8.64 4.57 8.64	485 485 485 485	13.1 12.1 18.3 14.7	6.26 13.88 3.21 9.41	[15,16]	
MB78	20	P	Extruded	S-T S-T	6.40 6.40	500 400	16.0 14.0	6.25 5.22	[17]	
MB85	15	P	-	L-T L-T L-T	- - -	387 373 435	29.7 36.3 22.0	- - -	[18]	No description of test procedure.
MB85	20	P	-	L-T L-T	- -	380 435	24.2 18.7	- -	[18]	No description of test procedure.
IN-9021	14	P	Extruded	L-T L-T	6.35 6.35	- -	13.4 13.8	- -	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
IN-9052	15	P	Extruded	L-T	6.35	450	8.9	-	[1,19]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.

* Round specimen of specified diameter tested.

TABLE 5. FRACTURE TOUGHNESS CHARACTERIZATIONS OF DISCONTINUOUS SiC REINFORCED CAST ALUMINUM ALLOYS

Alloy Matrix	Reinforcement		Material Form	Orientation	Specimen Thickness B (mm)	Yield Strength S_y (MPa)	Fracture Toughness K_c (MPa $\sqrt{m}$)	B/ $(K_c/S_y)^2$	Ref. No.	Comments
	%	Type								
2014	15	P	Cast & Extruded	L-T L-T	6.35 6.35	- 319	14.0 21.3	- 1.42	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
2014	25	P	Cast & Extruded	L-T L-T	6.35 6.35	- -	14.8 12.8	- -	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
2024	15	P	Cast & Extruded	L-T	6.35	-	16.2	-	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
7475	15	P	Cast & Extruded	L-T L-T	6.35 6.35	- 300	13.6 14.5	- 2.72	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
Al - 4 Mg	15	P	Cast & Extruded	L-T	6.35	-	12.2	-	[1]	K_c determined from failure conditions in fatigue crack growth test; data reported as K_{Ic}.
A356	30	P	Cast & Hipped	T-L & ST-L	22.10	377	18.6	9.08	[20]	Short rod tests; no fatigue precrack.
A357	10	P	Cast Cast/Hipped	- -	12.70 12.70	325 345	16.7 21.4	4.81 3.30	[21]	
A357	20	P	Cast Cast/Hipped	- -	12.70 12.70	331 359	18.2 18.8	4.20 4.63	[21]	
A357	30	P	Cast & Hipped	T-L & ST-L	22.10	205	22.0	1.92	[20]	Short rod tests; no fatigue precrack.

material also has a higher strength (557 MPa), but, nevertheless, is probably not a plane strain value.

Before discussing materials and processing factors which affect the fracture toughness of these materials, one final comment should be made regarding the data of Tables 2 through 5. This relates to identifying what valid plane strain K_{Ic} data are really available for these MMC's. From careful evaluation of test procedures and comparison to ASTM E 399, the following K_{Ic} values seem most appropriate for consideration as approximate upper limit values of plane strain fracture toughness for these selected systems:

Materials System		K_{Ic} (MPa·m$^{1/2}$)
Extruded	15% SiC_w/2124	21 [3]
Extruded	20% SiC_w/6061	15 [12]
Rolled	25% SiC_p/6061	16 [12]
Rolled	25% SiC_w/7090	8 [14]
Extruded	30% SiC_p/7091	14 [15,16]
Rolled	30% SiC_p/7091	18 [15,16]
Extruded	20% SiC_p/MB78	16 [17]
Cast/Hipped	10% SiC_p/A357	21 [21]
Cast/Hipped	20% SiC_p/A357	19 [21]

These are the only systems tested to date that satisfy valid plane strain criteria for identification of K_{Ic}. Much of the remaining data reflect K_c values generated on thin sections, and it is unclear how much improvements in fracture toughness in recent years are due to geometry or to real material improvements.

FACTORS AFFECTING FRACTURE TOUGHNESS

Keeping in mind the restrictions noted previously regarding valid plane strain fracture toughness data, the available data will be used to illustrate some of the major factors which are considered to influence the fracture resistance of these materials. The primary factors generally acknowledged to affect fracture toughness are:

(1) Material thickness
(2) SiC reinforcement effects
(3) Aluminum alloy chemistry
(4) Mechanical working and secondary processing
(5) Powder metallurgy vs. ingot metallurgy

Each of these factors is discussed briefly below.

Material Thickness. As with unreinforced metals, these MMC materials exhibit significant increases in fracture toughness as material thickness decreases below the plane strain level to the plane stress transition region. This is illustrated in Figure 1, where the K_c data of Tables 2 through 5 are plotted against the ratio $B/(K_c/s_y)^2$. For metals, the plane stress region B is normally identified (Damage Tolerant Design Handbook)as that region corresponding to a ratio value from 0 to 0.2, the plane stress to plane strain transition corresponding to a ratio from 0.2 to 2.5, and the plane strain region corresponding to a ratio greater than 2.5. As is evident from Figure 1, significant increases in K_c are not observed until this ratio is less than 1.5. However, it should be remembered that these data include various material types, conditions, and strength levels, and thus, this plot in Figure 1 is not a direct indication of plane stress to plane strain transition. Such an unambiguous plot is not readily available for any MMC, with the possible exception of 2124 Al reinforced with 15% SiC_w [6] (Advanced Composite Materials Corp., 1988).

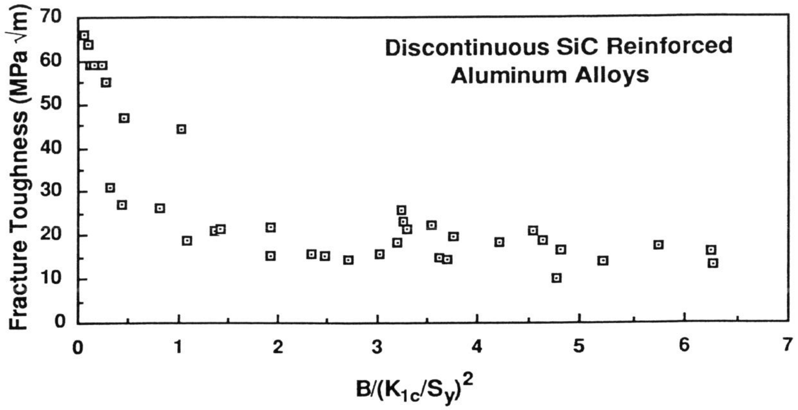

Figure 1. Fracture toughness vs $B/(K_{1c}/S_y)^2$ for discontinuous SiC reinforced aluminum alloys

SiC Reinforcement Effects. The SiC reinforcement effects dominate the fracture toughness behavior over other materials factors. Specifically, the major reinforcement factors affecting toughness include: reinforcement type (particulate vs. whisker), volume fraction, size, and dispersion (homogeneity). While the materials suppliers and users debate over whether particulate reinforced or whisker reinforced aluminums have inherently higher fracture toughness, unequivocal data to illustrate this effect appear nonexistent. Variations in material preparation techniques (e.q., rolling, extrusion, amount of work) and strength levels have precluded definitive comparisons. It is well known, however, that the whisker reinforced material is more directional in properties, thereby in general exhibiting poorer TL toughness than particulate reinforced material.

With regard to volume fraction of reinforcement,it is well recognized that lower volume fractions result in higher fracture toughness. Indeed, Advanced Composite Materials Corp. in conjunction with some of its customers, has directed its most recent activities at lower volume fraction MMC's in thin sections [4-6] (Advanced Composite Materials Corp., 1988; Cook and Mohn, 1987; Mohn and Vukobratovich, 1988). Reinforcement levels of 15% SiC have been observed to provide the best balance of toughness, strength, stiffness, and ductility in these whisker reinforced materials. For particulate reinforced materials slightly higher SiC levels appear to be possible.

Finally, SiC size, size distribution, and dispersion homogeneity have all been recognized as potentially significant factors influencing fracture toughness. In particular, obtaining homogeneous SiC dispersions has been identified as providing the best method of improving toughness in recent materials in contrast to earlier manufactured materials. Improvements in homogeneity have been attributed to both manufacturing methods and better awareness of aluminum powder and SiC reinforcement size and size distribution control.

Aluminum Alloy Chemistry. The aluminum alloys that have been used in all discontinuous SiC reinforced MMC's to date have been taken from existing aluminum chemistry used for either PM and IM unreinforced applications. With only a few exceptions have these basic chemistries been altered even slightly for a SiC reinforced application. With mounting evidence of solute diffusion both toward and away from SiC reinforcement interfaces and silicon depletion of SiC during MMC processing, increasing attention is being given to aluminum matrix chemistry specifically tailored for SiC reinforced MMC's.

The significance of alloy chemistry for improved fracture toughness can be seen in comparing the 2124 and 6061 PM data of Tables 2 and 3. The 2124 based MMC's have displayed higher toughness than the corresponding 6061 materials, being particularly higher in thinner sections where non-plane strain conditions exist. Alloy chemistry has also been recognized as very significant for melt processed materials where silicon depletion from SiC during high temperature treatments must be accomodated via matrix chemistry. This is discussed more fully in a later section.

Alloy chemistry that has been addressed in somewhat greater depth has been the restriction of minor element levels, such as Mn, and tighter controls on major alloy elements such as Cu ang Mg. These approaches have followed along the lines that have been used successfully for PM aluminum alloys in general. Although not strictly alloy chemistry, major improvements in these MMC's have also been achieved via better control of residual gas levels in the fabricated PM material compactions.

Mechanical Working and Secondary Processing. The amount of mechanical work that is given to these MMC's is a very significant factor influencing the mechanical properties. This mechanical work includes extrusion, rolling, etc., and applies to both PM and IM processed materials. In general, the greater the amount of work the better the mechanical properties, including fracture toughness. The increased amount of mechanical work primarily serves to homogenize the material and to refine the matrix microstructure through combined dislocation, precipitation effects. Excessive working can result in breaking up the SiC reinforcements and preferrentially orienting the reinforcements. These effects on reinforcements are most pronounced on the SiC whisker materials, which are noticeably anisotropic and which in effect become particulate in form if they are extruded and rolled to any great extent. The data tabulated in Tables 2 and 3 show these effects on fracture toughness (and yield strength) most clearly.

Secondary processing via heat treatments, mechanical working coupled with heat treatments, and thermomechanical methods have been investigated to a limited degree. It was found in the early studies of this decade that the SiC reinforcements accelerated the reaction kinetics appreciably in the aluminum matrices compared to the reinforced states. Thus, special heat treatments have been experimentally developed for the MMC's to achieve the peak strength condition in the most widely used alloys, such as 2124 and 6061. Little has been done beyond this in regard to heat treatments designed to improve fracture toughness. With regard to incorporating mechanical working or thermomechanical concepts to improve fracture toughness, less has been investigated in comparison to heat treatment methods. Certainly, new methods are in order which would effectively utilize or perhaps counterbalance the inherent effects caused by the large differences in thermal conduction and thermal expansion between the SiC reinforcements and the aluminum matrix.

Powder Metallurgy vs. Ingot Metallurgy. The present methods available for producing discontinuously reinforced MMC materials are limited to powder metallurgy and ingot metallurgy techniques. Utilizing the PM approach, a wide variety of materials can be produced including the high strength 7000 series materials as well as the elevated temperature aluminum alloys available by mechanical alloying. While PM MMC's can utilize both SiC whisker and SiC particulate reinforcements with the full range of alloys available, the IM MMC's are presently limited to using SiC particulate reinforcements in standard aluminum casting alloys with high silicon levels (i.e., A356 and A357) and Al_2O_3 reinforcements in wrought alloys with low silicon additions (2124 and 6061) (Schuster, 1988). Data in Table 5 illustrate the poor properties observed in earlier studies on IM materials based on 2XXX and 7XXX alloys.

Although the castable grades of MMC typically show inferior fracture toughness compared to PM grades, the majority of net-shape casting used in aerospace applications are in non-fracture critical areas. Thus, particularly in the A356 and A357 premium casting alloys reinforced with SiC particulate, the strength, modulus and ductility are the prime property requirements that must be met for optimum performance.

The major impetus for limiting SiC additions to alloys containing high slicon levels (>3-4%) in IM grades of MMC lies in the extreme temperatures (>700°C) used during primary fabrication of billets. In low silicon alloys such as 2024 and 6061, the driving force to remove silicon from the SiC particles is much higher than in the high silicon alloys typically used for netshape castings (Austin and Saathoff, 1988). The resulting degradation of the SiC interface by the formation of Al_4C_3 can result in lower ductility and concomitant decreases in ultimate strength when compared to PM grades of MMC.

Additionally, aluminum casting alloys with low silicon levels, such as A201, show that silicon leached from the SiC particles can also result in a reduction of the eutectic melting temperature. Differential Scanning Calorimetry results for a SiC reinforced A201 casting alloy (Austin and Saathoff, 1988) show the reduction in the eutectic melting as well as the a considerable changes in the precipitation kinetics compared to the unreinforced material. High silicon alloys such as A357 show only minor differences in the precipitation kinetics compared to the unreinforced material.

Other factors in the primary fabrication of IM MMC materials which affect final mechanical properties and fracture resistance include gas porosity, particle dispersion (solidification rate), and alloy cleanliness. The solidification rate and its concomitant effect on the final distribution of SiC,is extremely important in net-shape castings since additional thermomechanical processing is not available to redistribute the reinforcement as is the case with extrusions, sheet, and forgings. A slow solidification rate causes particulate to segregate along the solidification front producing a nearly continuous path for fracture. A faster solidification rate produces a more uniformly dispersed reinforcement which would exhibit higher fracture resistance (Chamberlain, 1988).

SUMMARY

A review of the open literature has shown that there have been relatively few fracture toughness determinations on discontinuous SiC reinforced aluminum alloys. Additionally, most of the data failed to pass ASTM E 399 criteria for plane strain. The MMC technical community must exercise much greater care in fracture toughness test procedures, data analysis, and reporting to resolve this unacceptable situation.

From the sparse data that does exist, it can be seen that substantial improvements have been achieved over material toughness levels observed at the beginning of this decade. However, some of these "improvements" are geometrically based (i.e., derived by avoiding plane strain thickness), and it is unclear how significant some of the improvements really are. Nevertheless, key factors which affect fracture toughness in these materials have been identified, and materials suppliers and their customers are becoming increasingly aware of controlling these factors for a better balance of mechanical properties.

REFERENCES

Advanced Composite Materials Corp. (1988). Engineering Data Leaflet.

L.K. Austin (1985). Fracture toughness enhancement in 30% SiC_p/7091 aluminum through thermomechanical processing. University of Texas at Arlington, Mech. Engr. Dept. Tech. Rept. No. 85-005 (M.S. thesis).

L.K. Austin and R.D. Goolsby (1986). Fracture toughness enhancement in 30% SiC_p/7091 Al through thermomechanical processing. Proceedings 31st International SAMPE Symposium. Society for the Advancement of Materials and Process Engineering, Covina, California.

L.K. Austin and W.M. Saathoff (1988). Net shape MMC structures for aerospace applications. 2nd SAMPE Metals and Metals Processing Conference, Dayton, Ohio. Society for the Advancement of Materials and Process Engineering, Covina, California.

W.F. Bates. Metal matrix composite structural demonstration program. Lockheed-Georgia Co., Air Force Contract No. F33615-81-C-3211.

J.R. Carroll. Structural advanced material/manufacturing development. Lockheed-Georgia Co., Air Force Contract No. F33615-80-C-3282.

B. Chamberlain (1988). Alcan Aluminum Corp., unpublished data.

D.J. Chellman (1985). Development of 2XXX series Al/SiC composite materials for high temperature aircraft structural applications. Lockheed- California, Burbank, California, NASA contractor report 172522.

J.L. Cook and W. R. Mohn (1987). Whisker-Reinforced MMC's. In: Engineered Materials Handbook, Vol. 1, Composites, pp. 896-902. ASM International, Metals Park, Ohio.

C.R. Crow, R. A. Gray, and D. F. Hasson (1985). Microstructure controlled fracture toughness of SiC/Al metal matrix composites. Proceedings Fifth International Conference on Composite Materials, ICCM-V. (Eds. W. C. Harrigan, Jr., J. Strife, and A. K. Dhingra), pp. 843-866. Metallurgical Society of AIME, Warrendale, Pennsylvania.

Damage Tolerant Design Handbook(1975). Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio.

D.L. Davidson (1987). Fracture characteristics of Al-4 pct. Mg mechanically alloyed with SiC. Metall. Trans. A, 18A, 2115-2128.

D.L. Davidson (1987). Micromechanisms of fatigue crack growth and fracture toughness in metal matrix composites. Southwest Research Institute Report 06-8602/2, ONR Contract N00014-85-C-0206.

A.P. Divecha, S. G. Fishman, and S. D. Karmarkar (1981). Silicon carbide reinforced aluminum - a formable composite. J. Metals, 33, 12-17.

R.D. Goolsby (1983). University of Texas at Arlington, previously unpublished data on particulate reinforced 6061 aluminum.

R. D. Goolsby (1985). University of Texas at Arlington, previously unpublished data on particulate and whisker reinforced 6061 aluminum.

R.D. Goolsby and L. K. Austin (1984). Fracture toughness and fatigue crack growth evaluations of 25% SiC_w/7090-T6 Al sheet and plate. University of Texas, Mech. Engr. Dept. Tech Rept. No. 84-001

R.D. Goolsby and J. L. Petty-Galis (1986). University of Texas at Arlington, previously unpublished data on whisker reinforced 2124 aluminum.

T. Gurganis (1988). Alcoa Corp., private communication. W. C. Harrigan (1988). DWA Composite Specialities, Inc., private communication.

D.F. Hasson, S. M. Hoover, and C. R. Crowe (1985). Effect of thermal treatment on the mechanical and toughness properties of extruded SiC_w/aluminum 6061 metal matrix composite. J. Mater. Sci, 20, 4147-4154.

A. Marchand, J. Duffy, T. A. Christman, and S. Suresh (1988). An experimental study of the dynamic mechanical properties of an Al-SiC_w composite. Engr. Fract. Mech., 30, 295-315.

W.R. Mohn and D. Vukobratovich (1988). Engineered metal matrix composites for precision optical systems. SAMPE J., 24, 26-35.

Plane-strain fracture toughness of metallic materials. ASTM Standard Test Method E 399. American Society for Testing and Materials, Philadelphia, Pennsylvania.

D.M. Schuster (1988). The Commercialization of MMC's produced by ingot metallurgy. 2nd International SAMPE Conference, Dayton, Ohio. Society for the Advancement of Materials and Process Engineering, Covina, California.

J.K. Shang, W. Yu, and R. O. Ritchie (1988). Role of silicon carbide particles in fatigue crack growth in SiC-particulate-reinforced aluminum alloys. Mater. Sci. Engr. A102, 181-192.

T.E. Steelman, A. D. Bakalyar, and L. Konopka (1987). Aluminum matrix composite structural design development. Rockwell International Corp., Air Force Wright Aeronautical Laboratories Rept. AFWAL-TR-86-3087.

J.J. Stephens, J. P. Lucas, and F. M. Hosking (1988). Cast Al-7 Si composites: effect of particle type and size on mechanical properties. Scripta Metall.,22, 1307-1312.

N. Tsangarakis, B. O. Andrews, and C. Cavallaro (1987). Mechanical properties of some silicon carbide reinforced aluminum composites. J. Composite Mater., 21, 481-492.