Conf-940204--5

UCRL-JC-115698
PREPRINT

Influence of Volume Fraction of Component Materials and Interlayer Bond Strength on Fracture Toughness of Multi-Layer Al 6090-25 vol. % SiCp and Al 5182 Laminates

C. K. Syn
S. Stoner
D. R. Lesuer
O. D. Sherby

This paper was prepared for submittal to the
Minerals, Metals and Materials Society Conference on High Performance Ceramic and Metal Matrix Composites
San Francisco, CA
February 27-March 3, 1994

November, 1993

Lawrence Livermore National Laboratory

DISCLAIMER

November 16, 1993

Prepared for TMS Conference on High Performance Ceramic and Metal Matrix Composites
February 27-March 3, 1994, San Francisco.

Influence of Volume Fraction of Component Materials and Interlayer Bond Strength on Fracture Toughness of Multi-Layer Al 6090-25 vol.% SiCp and Al 5182 Laminates*

C. K. Syn†, S. Stoner†, D. R. Lesuer†, and O. D. Sherby‡
†Lawrence Livermore National Laboratory, Livermore, CA 94550
‡Department of Materials Science and Engineering
Stanford University, Stanford, CA 94305

Abstract

Multilayer laminates of Al 6090/SiC/25p MMC and Al 5182 were prepared by hot pressing alternating layers of the component materials at 450°C in an argon gas atmosphere. Tensile properties, interlayer normal and shear bond strengths, and fracture toughness were measured in the T6-treated and untreated conditions. Fracture toughness was also measured as a function of the volume fraction of the MMC component. Yield and tensile strengths increased substantially by the T6 treatment while the total elongation and interlayer bond strengths decreased even more substantially. Fracture toughness, on the other hand, did not change appreciably by the T6 treatment. The fracture toughness increased perceptibly with an increase in the volume percent of the MMC component.

*Work performed under the auspices of of the U.S. Department of Energy by the Lawrence Livermore National Laboratry under contract No. W-7405-ENG-48.

Introduction

Metal matrix composites (MMCs) are generally recognized for their high specific strength or stiffness and the capability to achieve certain prescribed performance characteristics. However, for structural applications, most of these materials can benefit from improvements in certain damage critical properties such as fracture toughness. Structural factors that influence the fracture resistance in discontinuously reinforced aluminum (DRA) materials have been recently reviewed by Hunt et al[1]. Making laminated composites consisting of reinforced and unreinforced alloys has been identified as one of the effective ways for the toughness enhancement. In fact, it has been demonstrated that the fracture toughness[2-4] of 6090/SiC/25p MMC and the Charpy impact energy[5, 6] of X7093/SiC/15p MMC can be substantially increased by laminating with 5182 and X7093, respectively.

It has been shown that laminates of metal-base alloys exhibit substantial increases in toughness[7, 8], in Charpy impact energy and in reductions of the ductile-brittle transition temperature[9, 10]. Interfaces in these laminates were observed to delaminate during the crack propagation. Such delaminations were shown to eliminate the triaxial stress state[7, 9], leading to plane-stress fracture condition[7, 9], and to blunting[11, 12] or deflection[12] of the crack. Similar behavior was observed in laminates of DRA interleaved with the matrix alloy[5, 6] or other with Al alloys[2-4].

The purpose of this paper is to investigate the fracture toughness and behavior of multi-layer laminated metal composites (LMCs) containing Al 6090/SiC/25p MMC and Al 5182 of varying volume fractions and interlayer bond strengths. Fracture surface morphology, delamination behavior, tensile ductility and toughness values of the laminates are compared in the as-processed and in the T6 heat treated condition.

Experimental Details

Materials:

An Al 6090/SiC/25p MMC was obtained from a commercial source in the form of 2.6, 6, and 10 mm thick warm or hot rolled sheets. Al 5182 was obtained from a different commercial source in the form of warm or hot rolled sheets of 0.25, 2.1, and 2.6 mm thicknesses. Both materials were sliced to 51 mm x 51 mm squares and chemically cleaned to remove the surface oxide scale. No heat treatment was performed prior to lamination.

Processing:

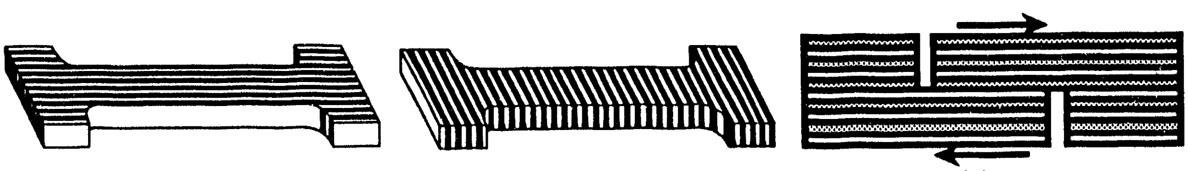
Laminates were fabricated by preparing stacks of the component material layers assembled in an alternating sequence. Each stack was hot pressed from an initial thickness of about 50 to 60 mm to a final thickness of about 15 to 17 mm resulting in about a 3.5/1 thickness reduction. Such a large reduction by plastic deformation ensured good bonding at interfaces. All pressing was performed at 450°C in an argon gas atmosphere. General guidelines for processing and additional details concerning the materials and processing are described elsewhere[3].

After deformation processing, some of the Al laminates were heat treated by soaking at 530°C for 75 minutes, water quenching and then aging at 160°C for 16 hours. This procedure provided a T6 heat treatment to the 6090-25 vol.% SiC_p layers while not affecting the 5182 layers.

Mechanical Property Tests

Tensile Tests. The tensile stress-strain behavior of the component materials and laminates was characterized using flat tensile specimens. The tensile axis was parallel to the rolling direction of the original sheet materials. Test specimens, see Fig. 1(a), of 12.7 mm gage length and 5.08 mm gage width were machined by the EDM method. Specimen thickness was 3.175 mm for the press-bonded laminates and equal to the thickness of the plate for the component materials. Tensile tests were conducted at room temperature at a nominal strain rate of 4×10^{-4} sec^{-1} using an Instron machine.

Bond Strength Tests: The interlayer interfacial bond strength of the laminates was evaluated by using tensile and shear specimens. The gage length, width, and thickness of the "normal" tensile test specimens, see Fig. 1(b), were 3.2 mm, 2.5 mm, and 5.1 mm, respectively. The thickness, width, and length of the shear test specimens , see Fig. 1(c), were 5.1 mm, 10.2 mm, and 25.4 mm, respectively, and the separation between the two slots was 5.1 mm. Both the "normal" tensile and "lap" shear tests were conducted at room temperature at a nominal strain rate of 4×10^{-4} sec^{-1} on an Instron machine. The normal and shear bond strengths were calculated,from the loads at which the fracture or shear separation occurred at an interface within the gage length.



(a) (b) (c)

Fig. 1. Geometries of tensile samples in the parallel (a) and normal (b) orientations and the lap shear test sample (c).

Fracture Toughness Tests. The size of the laminates prepared precluded the use of full size fracture toughness test specimens. Toughness for press-bonded laminates was measured by using subsized chevron notch three-point bend bars as illustrated in Fig. 2. The depth, thickness, and span length of the chevron-notch bend bars were 10.2 mm, 15.2 mm, and 61.0 mm, respectively. Since a laminate is highly anisotropic, the orientation of a test specimen with respect to the layers of the laminate can have a large effect on the toughness. In the present study, specimens of the "crack arrester" and "crack divider" orientations[4, 9] were prepared. Since no standardized test procedure for the chevron-notch bend bars has been established, the procedure described by Wu[13] was followed. The procedure does not require fatigue pre-cracking of the test sample. The maximum load of the load-crack opening displacement curve was used to calculate the fracture toughness

Fractography:

Tensile and fracture toughness tested samples were examined by optical and scanning electron microscopy to determine the fracture and interface delamination behavior. Tensile tested samples were cross-sectioned for further investigation of the delamination and microstructural fracture behavior.

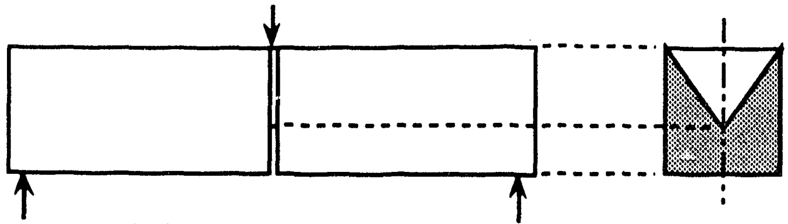


Fig. 2. Chevron-notch three-point bend bar specimen for fracture toughness tests. Arrows represent the loading points and directions. The darkened area corresponds to the machined chevron notch.

Results

Structure.

A typical as-pressed Al laminate after its edges were trimmed is shown in Fig. 3. Dark layers in Fig. 3 represent the Al 6090/SiC/25p and light layers Al 5182. The laminate shown in Fig. 3 has ten layers of Al 6090/SiC/25p and eleven layers of Al 5182 constituting a nominal 50-50 volume percent laminate. Microscopy of the interlayer boundary in the as-processed or T6 treated laminates showed no unbonded areas, as reported elsewhere[3].

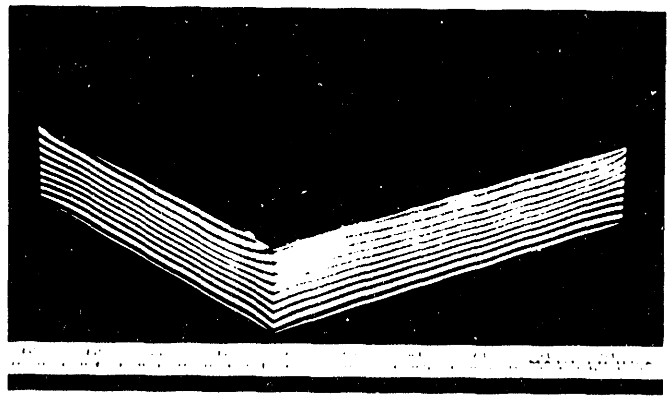


Fig. 3. Example of as-pressed Al laminate.

Tensile Properties.

Tensile properties are summarized in Table 1 for the laminates containing 50-50 volume percent of the component materials in the as-bonded and T6 treated conditions. Table 1 also includes the tensile properties of the component materials for comparison. Tensile properties are listed here as a data base for subsequent discussion of the fracture behavior later. The T6 treatment increased the yield and tensile strengths by ~30% . The total elongation or ductility after the T6 treatment was reduced to about 7% from that of about 17% in the as-pressed condition in the laminate, but is still more than 100% higher than that of the 6090/SiC/25p component.

Table 1. Tensile properties of Al 6090/SiC/25p-Al 5182 laminates containing of 50-50 volume percent of the component materials and component materials

Processing	Average Layer Thickness, μm	Yield Strength MPa(ksi)	Ultimate Tensile Strength, MPa(ksi)	Elongation %
As-Pressed	750	162(23.5)	266(38.5)	16.9
Pressed, T6	750	232(33.6)	333(48.2)	7.2
Al 5182	-	130(18.9)	275(39.9)	25
Al 6090/SiC/25p	-	265(38.4)	310(45.0)	4
Al 6090/SiC/25p, T6	-	422(61.2)	510(72.7)	3.2

Bond Strength:

Bond strengths were measured for the 50-50 volume percent laminates in the as-pressed and T6 treated conditions, and the results are plotted in Fig. 4. Fig. 4 shows that substantial reductions [~70% for the "normal" and ~40% for the "shear" directions] in the interfacial bond strengths after the T6 treatment, indicating that the T6 treatment can be an effective way to change the interfacial bond strength of these Al laminates.

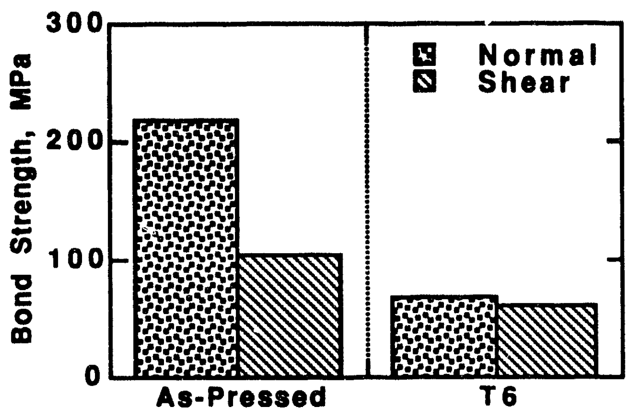


Fig 4. "Normal" and "shear" interface bond strengths before and after the T6 heat treatment.

Fracture Toughness:

Toughness values measured for the 50-50 volume percent laminates with and without the T6 treatment are shown in Fig. 5 for the crack divider (C. D.) and crack arrester (C. A.) orientations. Fracture toughness of the component materials, Al 6090/SiC/25p MMC with T6 treatment, and Al 5182, was not measured in the present study, mainly due to the lack of sufficiently thick materials. For the Al 6090/SiC/25p MMC component, two toughness values have been reported[14, 15], and the higher value of the two is included in Fig. 5. Since the toughness value for the Al 5182 component is not available in literature, the value for Al 5083 H321[16], whose composition is rather close to that of the Al 5182 is used in Fig. 5.

The toughness of the laminates does not change noticeably from the average value of ~30±1 $MPa \cdot m^{1/2}$ regardless of the T6 treatment for both crack divider and arrester orientations. These results contrast with the substantial change in the tensile properties and interfacial bond strengths before and after the same T6 treatment.

The fracture toughness variation for both crack divider and arrester orientations as a function of the volume percent of the MMC component is shown in Fig. 6 for the T6 treated laminates. It is significant to note that the toughness shows a slight but definitely increasing trend with the volume percent of the MMC component for both orientations. The horizontal axis in Fig. 6 also shows the global volume percent of the SiCp reinforcement.

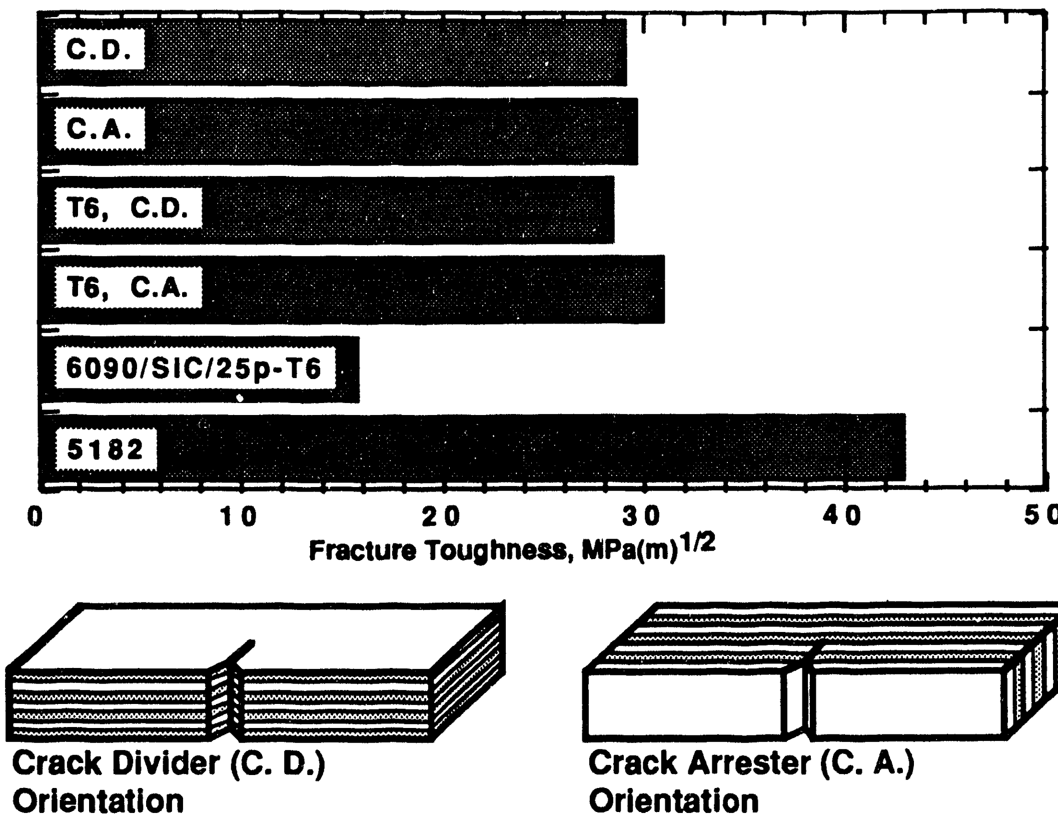


Fig. 5. Fracture toughness of Al 6090/SiC/25p-Al 5182 laminates (containing 50-50 volume percent of the component materials) with and without T6 treatment for the crack divider (C. D.) and crack arrester (C.A.) orientations.

Fracture Behavior:

Fracture surfaces of tensile and fracture toughness tested samples and cross-sectional microstructures of tensile tested samples were examined to determine fracture morphology and the interfacial delamination behavior of the laminates. Fig. 7 represents the cross-sectional views of the tensile tested samples in the as-pressed and T6-treated conditions. It is clearly seen in Fig. 7 that the T6 treatment leads to large scale interfacial delamination as a result of the reduction in interfacial bond strength [Fig. 4]. Despite the large effect of the T6 treatment on the delamination behavior in the tensile tested samples, the influence of such treatment on the fracture surface seems to be rather subtle. Fig. 8 shows the fracture surfaces of the laminates with 50-50 volume percent in the as-pressed [Fig. 8(a)] and T6-treated [Fig 8(b)] conditions when tested in the crack arrester orientation. In Fig. 8, the fracture crack was initiated in the lower right hand corner and propagated to the upper left hand corner. In the as-pressed condition, every other interface of the layers was delaminated while every interface was separated in the T6-treated condition. Fig. 9 shows the fracture surface morphology of the laminates in the T6 treated condition with 50, 75, and 97 volume percent of the MMC component. Results are given for the crack divider orientation. Every interlayer interface is seen to have delaminated. Every Al 5182 and 6090 MMC layer shows a shear fracture mode. For the 97%-3% laminate the rather thick MMC layers exhibited tensile fracture in the early stage of crack growth but immediately transitioned to the shear fracture mode.

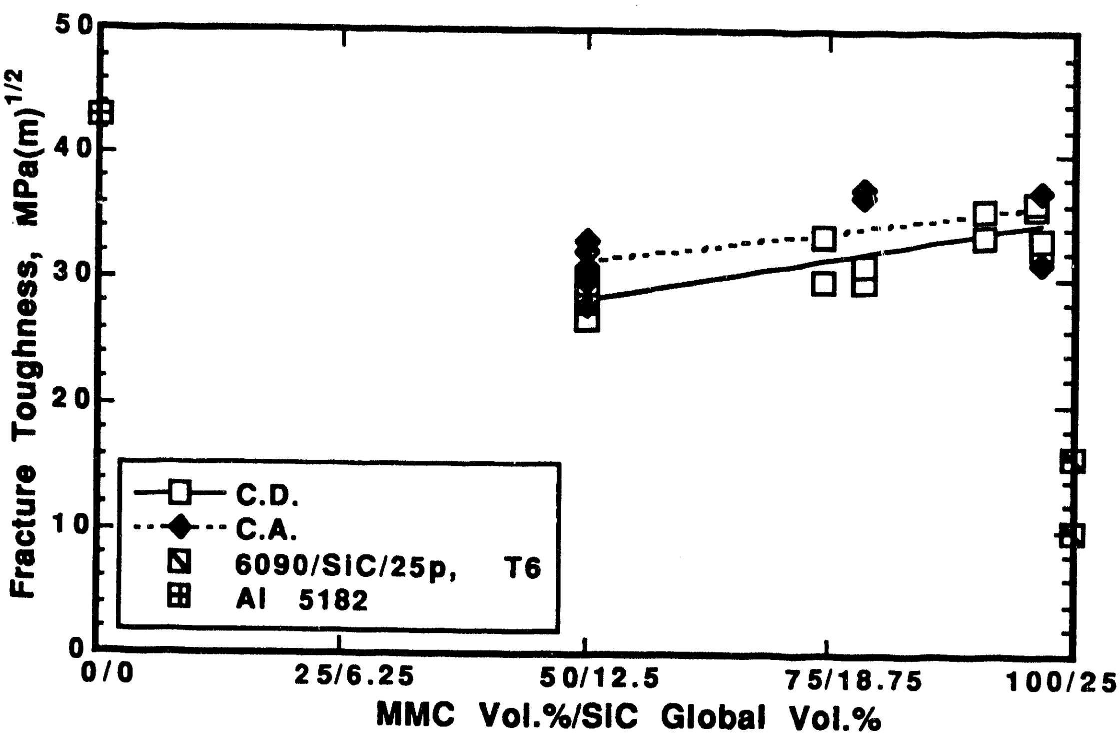


Fig. 6. Fracture toughness of Al 6090/SiC/25p-Al 5182 laminates versus the volume percent of the MMC component and the global volume percent of the SiCp reinforcement.

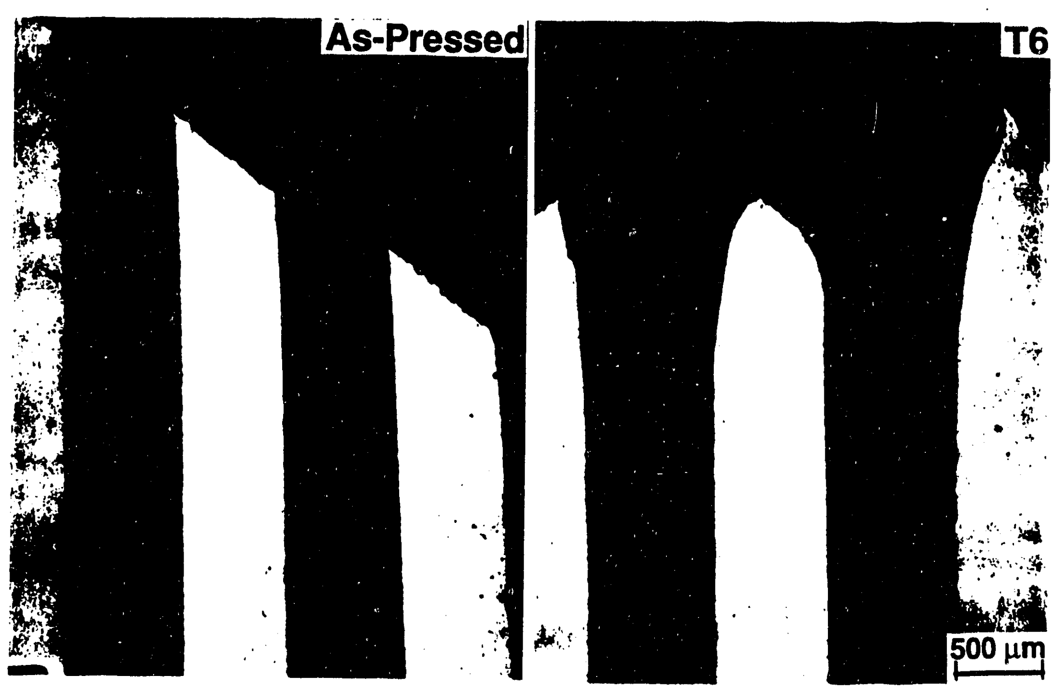
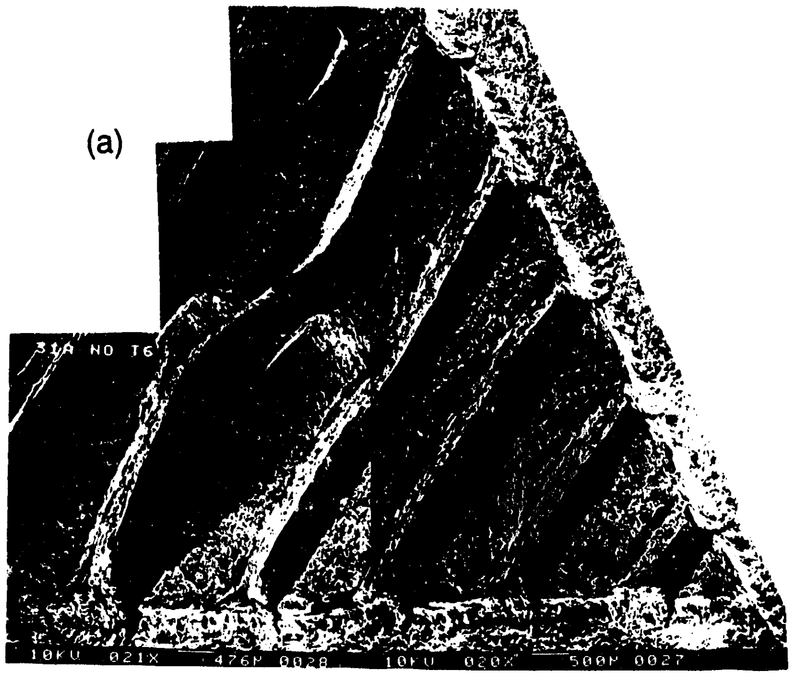


Fig. 7. Cross-sectional views of tensile tested laminates with and without T6 treatment.

(a)



(b)

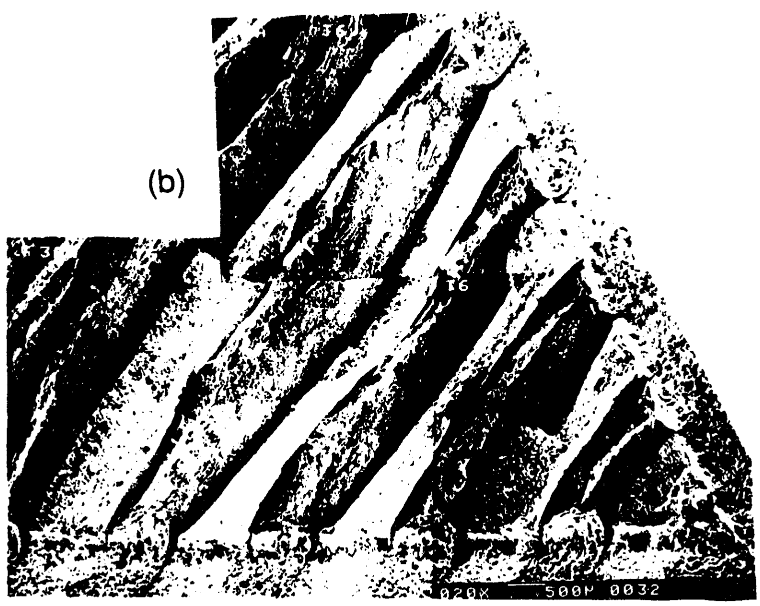


Fig. 8. Fracture surfaces of the 50-50 volume percent laminates in the as-pressed (a) and T6-treated (b) conditions for the crack arrester orientation. Direction for crack propagation is from the lower right-hand to the upper left-hand corners in both (a) and (b).

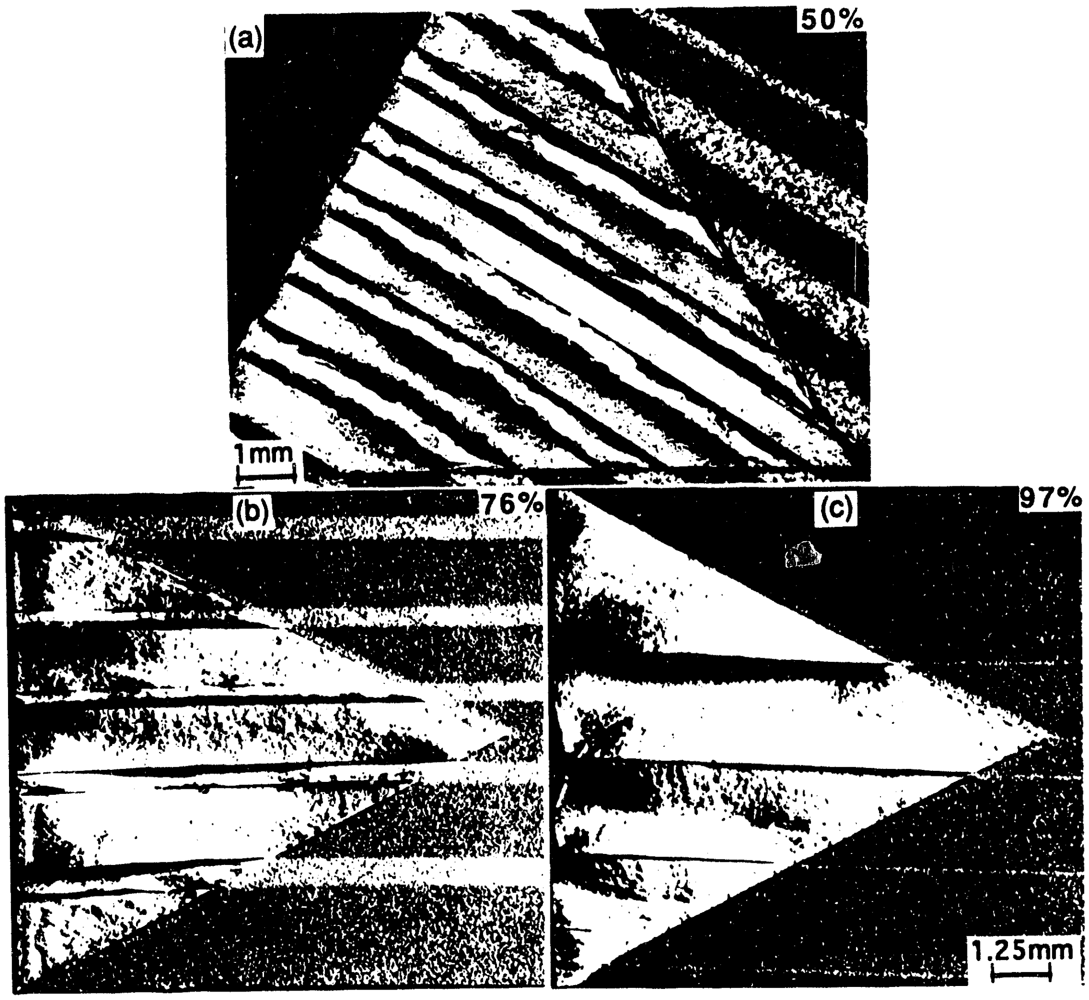


Fig. 9 Fracture surface of the T6-treated laminates with (a) 50, (b) 75, and (c) 97 vol.% of the MMC component tested in the crack divider orientation.

Discussion

Influence of T6 Treatment on Toughness:

The toughness values plotted in Fig. 5 are not the plane-strain fracture toughness values represented by K_{Ic}. If the values in Fig. 5 are to be qualified as the K_{Ic} values obtainable by testing full-size compact tension type specimens, then the test specimen thickness should be at least 19 mm and 40 mm for the T6 treated and untreated laminates, respectively. Nevertheless, Table 1, Fig. 4 and Fig. 5 do show that the yield and tensile strengths for laminates of a given thickness [in the present case, about 15 mm] can be dramatically increased by giving a T6 treatment without losing toughness. Results in Figs. 4 and 5, on the other hand, show that the interfacial bond strength can be drastically reduced by the T6 treatment without losing the toughness.

Toughness vs. MMC Vol.%:

Results in Fig. 6 clearly shows that with lamination the fracture toughness of 6090/SiC/25p MMC can increase with increasing global volume percentage of reinforcement. An increased volume percent of the MMC or global volume percent of the SiCp reinforcement will also lead to increased yield and tensile strengths of the laminate. Tensile properties of a composite material are known to follow the rule-of-average of those of the component materials[17]. These results indicate that with lamination technology both fracture and tensile strengths can be enhanced by increasing the volume percent of MMC or reinforcing agent. The global volume percent of the reinforcing agent in a lamiante may be increased by using an MMC that contains a higher volume percent reinforcement.

Delamination and Fracture Behavior:

Delamination [Fig. 7(b)] in the T6-treated tensile specimens and its absence [Fig. 7(a)] in the untreated ones seem to correlate well with the tensile ductility measured in these samples. The T6-treated specimens showed a much lower elongation than the untreated ones [Table 1]. Syn et al[18] in their study on ultrahigh carbon steel (UHCS)-brass laminates with different layer thicknesses showed that delaminated layers fail by necking in the ductile component (brass) and tensile fracture in the brittle component (UHCS), while undelaminated layers suppress necking or brittle tensile fracture in the adjacent UHCS layers resulting in enhanced ductility. One can clearly identify such behavior in the samples shown in Fig. 7(a) and (b). The fracture profile in the undelaminated sample in Fig. 7(a) essentially follows a 45° path, while the fracture profile in the delaminated sample shows necking to a point in the ductile Al 5182 layers.

Delamination is observed at every interlayer interface in the fracture toughness specimens of the T6-treated laminates as shown in Figs. 8(b) and 9. Delaminated layers fracture initially in a flat tensile mode, but rapidly transition to rather ductile energy-consuming shear fracture mode, even in the laminates with thick brittle MMC layers such as in the 97%-3% laminate. As can be seen in Fig. 9(c), the MMC layer thickness (~2.0 mm) is greater than the thickness (0.7 mm) required in the toughness test specimens of the Al 6090/SiC/25p MMC itself for the plain strain fracture toughness. Such thick MMC layers in the laminate would have failed in brittle tensile fracture in thick layer laminates, but instead they transition to a shear fracture mode.

Delamination on every other interface in the as-pressed laminates shown in Fig 8(a) is related to the interfacial bond strength and the ease of crack propagation characteristics. A similar delamination behavior was observed in the UHCS-brass laminates[18] described above. When the crack enters a brittle layer of the MMC component, it creates a large stress concentration ahead at the next MMC-5182 interface and delaminates it. But such a delamination blunts the propagating crack, and further propagation of the fracture crack has to be re-initiated in the next layer of ductile 5182. The stress concentration field generated at the next 5182-MMC interface ahead of the regenerated crack in the ductile 5182 layer will be accommodated by large plastic deformation in the 5182 layer. The high bond strength at the 5182-MMC interface will force the two layers to deform and/or break together in the as-pressed laminate. But the T6 treatment apparently lowers the bond strength and allows delamination at such 5182-MMC interfaces as is shown in Fig. 8(b).

Fracture and Toughening Mechanisms:

The interlayer interface delamination instigates not only the crack blunting, but also the crack deflection by inducing shear fracture in the brittle MMC layers as shown in Figs. 8 and 9 . Incorporation of ductile interleaving layers further enhances the effects of blunting and deflection by plastic deformation. Ductile interleaving layers can also retard crack propagation by bridging the crack behind the crack front. Evidence of large plastic deformation and ductile rupture in the Al 5182 layers shown in Figs. 8 and 9 indicates clearly that crack bridging has occurred during the fracture of the laminates. Crack bridging by ductile layers has been demonstrated in bend testing of UHCS-brass laminates[3, 19] in the crack arrester orientation. Similar behavior was shown in three layer laminates of Al X7093/SiC/15p-Al X7093 for the crack divider orientation in which the crack front was pinned in the ductile layers of Al X7093. Crack bridging effects of a ductile component in other composite materials have been observed and analyzed extensively[20].

It seems certain that the fracture toughness of laminated materials is determined by several simultaneously or sequentially operating mechanisms. The relative dominance of these mechanisms can be changed by the relative strengths of the component materials and the interface bond strength. An example of the interdependence of interface and component material properties is available from the data in Figs. 4 and 5 and Table 1. Heat treatment decreases the interfacial bond strength (which should increase toughness) and increases the flow stress of the 6090 containing layers (which should decrease toughness). The net result of these two competing effects is shown in Fig. 5 - the toughness has changed very little with heat treatment. Nonetheless the results shown in Fig. 5 indicate that the laminated composites are very forgiving about the influence of heat treatment and other processing variables as long as the layers are reasonably well bonded to insure the structural integrity as shown elsewhere[2-4].

Nature of the Toughness Measured:

As discussed above, interlayer delaminations occur during the test as the crack initiates and propagates. It has been observed during the tests using compact tension type specimens that a slight change of the slope or a load drop in the load-crack opening displacement curve occurs when a crack initiates [known as a pop-in] or a delamination takes place. It was shown[7] that the toughness measured from the pop-in load did not change regardless of layer thickness but the toughness calculated from the maximum load increased with the decrease in the layer thickness. The toughness obtained from the pop-in load was interpreted to represent the crack initiation toughness and the toughness from the maximum load correspond to the crack growth toughness[1, 6, 21]. Such an interpretation seems inherently correct. Toughness values measured with the present chevron notch bend bar samples are likely to represent the crack growth toughness.

Summary and Conclusions

Multilayer laminates of Al 6090/SiC/25p MMC and Al 5182 were prepared by press bonding at 450°C. Tensile properties and fracture toughness were measured for T6-treated and untreated conditions, and also for different volume fractions of the component materials. The conclusions are as follow:

1. The T6 treatment increases the yield and tensile strengths by about 30%, but decreases he total elongation by 60% and the interlayer interface bond strength by

about 70% for the direction normal to the layers and by about 40% for the shear direction.

2. The T6 treatment induces interlayer delamination in tensile tests and more extensive delamination in fracture toughness tests.

3. Fracture toughness for the 50-50 volume percent laminateswas about 30 ± 1 MPa·$m^{1/2}$ regardless of the heat treatment or testing direction.

4. The fracture toughness increased perceptibly as the volume percent of the MMC component increased from 50% to 97%.

Acknowledgment

The authors thank Chris Steffani, Ralph Otto, Gene Stebbins, Will Andrade, Jim Ferreira, and Al Shields for preparing laminates, machining test samples, metallography and fractography, and property measurements. The authors are grateful to Kevin Brown of Kaiser Aluminum, Center for Technology for 5182 materials and helpful discussion, with Warren Hunt of Alcoa, Alcoa Technical Center.

References

1. W. H. Hunt, Jr., T. M Osman, and J. J. Lewandowski, JOM, 45 (1993), No. 1, pp. 30-35.
2. C. K. Syn, D. R. Lesuer, K. L. Cadwell, O. D. Sherby, and K. R. Brown, Developments in Ceramic and Metal Matrix Composites, ed. K. Upadhya, TMS, 1991, pp 311-322.
3. C. K. Syn, D. R. Lesuer, and O. D. Sherby, Adv. Synthesis of Engineered Structural Materials, eds. J. J. More, E. J. Lavernia, and F. H. Froes, ASM Int'l, 1992, pp. 149-156.
4. C. K. Syn, D. R. Lesuer, and O. D. Sherby, Proc. Int'l Symp. on Light Materials for Transportation Systems, N. J. Kim, ed., Kyongju, Korea, June 20-23, 1993, pp. 763-771.
5. L. Y. Ellis, M.S. Thesis, Case Western Reserve University, 1992.
6. T. M. Osman, M.S. Thesis, Case Western Reserve University, 1993.
7. J. G. Kaufman, J. Basic Engineering, Trans. ASME, 1967, July, pp. 503-507.
8. J. A. Alic and A. Danesh, Eng. Fracture Mechanics, 10 (1978), pp. 177-186.
9. J. D. Embury, N. J. Petch, A. E. Wraith, and E. S. Wright, Trans. TMS-AIME, 239 (1967), pp. 114-118
10. D. W. Kum, T. Oyama, J. Wadsworth, and O. D. Sherby, J. Mech. Phys. Solids, 31 (1983), pp. 173-186.
11. J. Cook and J. E. Gordon, Proc. Royal Soc. London, 282 (1964), pp. 508-520.
12. R. O. Ritchie, W. Yu, and R. J. Bucci, Eng. Fract. Mechanics, 32 (1989), pp. 362-377.
13. S. X. Wu, Chevron Notched Specimens: Testing and Stress Analysis, J. H. Underwood et al. eds., ASTM-STP 855, Am. Soc. Testing. and Materials, 1984, pp. 176-192
14. Y. Flom and R. J. Arsenault, JOM, 38 (1986), No. 7, pp. 31-34.
15. M. G. McKimpson, E. L. Pohlenz and S. R. Thompson, JOM, 45 (1993), No. 1, pp. 26-29.
16. Wrought Aluminum Selector Chart, in Structural Alloys Handbook 1992, MCIC, J. H. Holt, H. Mindlin and C. Y. Ho, eds, CINDAS/Purdue University, West Lafayette, IN.
17. S. Lee, J. Wadsworth, and O. D. Sherby, J. Composite Mat'ls, 25 (1991), pp. 842-853.
18. C. K. Syn, D. R. Lesuer and O. D. Sherby, Met. Trans. A, 24A (1993), pp. 1647-1653.
19. Y. Ohashi, J. Wolfenstine, R. Koch, and O. D. Sherby, Mat. Sci. Eng., A151 (1992), pp. 37-44.
20. M. F. Ashby, F. J. Blunt, and M. Bannister, Acta Met. 37 (1989), pp. 1847-1857.
21. W. H. Hunt, Jr., Proc. Conf. Processing and Fabrication of Advanced Materials, Materials Week '93, October 18-21, 1993, Pittsburgh, in press.

END

DATE FILMED

4/6/94