A PRACTICAL ASSESEMENT OF FIBER REINFORCED ALUMINUM MATRIX COMPOSITES

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Composites have been developed with great success by the use of fiber reinforcements in polymer matrix materials. However, due to the limitation of some properties of polymer matrices, intense exploration on the use of metallic matrices has ensued, particularly with respect to aluminum. Several challenges stand in the way of production, such as higher processing temperatures, fiber/matrix bonding issues, and the ability to produce desired geometries. However, these problems are being solved and the present paper reviews the current state of the production of fiber reinforced metal matrix composites in addition to an introductory review of fiber composites in general. Based on current research, the future of these materials lies in the ability to economically produce desired shapes by pressure infiltration systems, and the need for improvement in fiber/matrix bonding and perhaps significant alloy development.

Introduction

In a world of materials there are many choices to suit many needs: for buildings concrete is used, for machines steel, for packaging plastics and cardboard, etc. All of these materials have specific properties that make them useful for some applications, and not useful for others. So what is done when an application exists where no one material exhibits the desired properties? Different materials with the desired properties are combined to meet this need, and the resulting material is a composite. Composites are seen in many applications, from the mundane such as fiberglass used in shower enclosures and skateboards, to highly engineered composites used in today's most modern airplanes.

Composites are typically used in applications where a material of high strength and low weight is desired. For instance, while metals typically have high strength, they are among the heaviest materials. Plastics, while very light, tend to be comparatively weak. Ceramics in fiber form, while very strong, lack rigidity without additional support. Then, if these ceramic fibers are placed in plastics, the fibers can carry most of the force, while the plastic helps the fibers maintain the desired useful shape. Figure 1 shows a simple fiber reinforced composite.

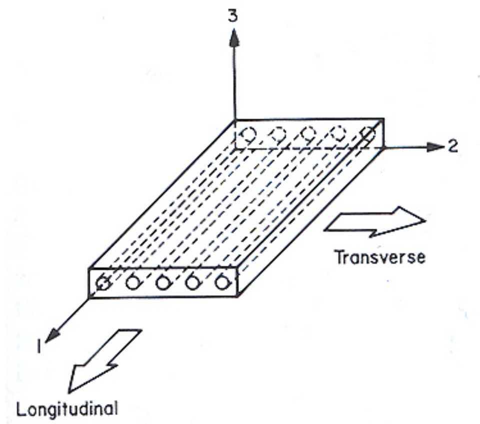


Figure 1: Schematic of fiber reinforced composite lamina with loading directions indicated (Agarwal and Broutman, 1990).

Composite Properties

The final properties of a composite are determined by fiber content, matrix material, fiber material, fiber orientation, and to a smaller extent by the fiber length and distribution in the composite. The reinforcing effects of the fiber in the composite are best explained by the rule of mixtures. In this rule, the properties of the composite depend directly on the volume fractions of each component in the mixture and the respective properties of the fiber and the matrix.

$\sigma_c = \sigma_f V_f + \sigma_m V_m$ and $E_c = E_f V_f + E_m V_m$

Where σ = Strength of the material, V= Volume fraction of component, E=Modulus of elasticity of the material. The subscripts c is for the finished composite, f is for the fiber, and m is for the matrix. Figure 2 illustrates the result on strength and modulus of the combination of properties in the composite. The effects of increasing the amount of fiber in the composite are illustrated in figure 3. At zero reinforcement the composite has the strength of the matrix, while as the content of fibers is increased (volume fraction), it increases in a linear manner that would reach the strength of the fibers at 100% fiber content if this condition were possible.

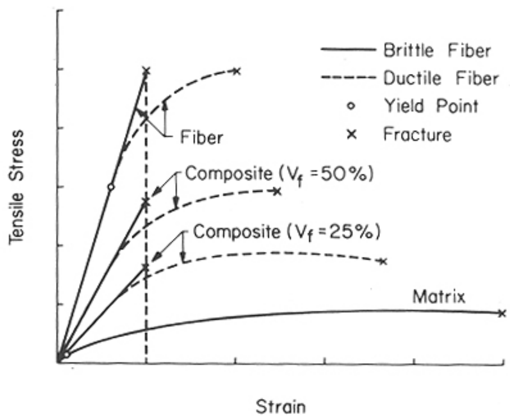


Figure 2: Properties of the composite based on the properties of the component materials (Agarwal and Broutman, 1990).

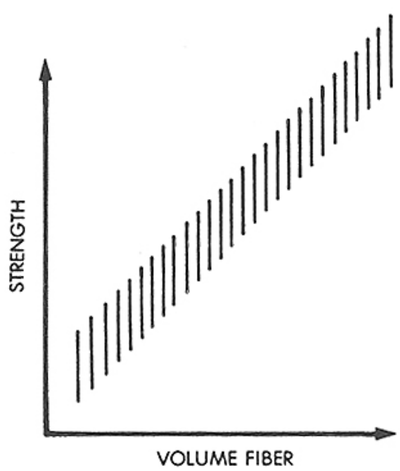


Figure 3: As fiber content increases the strength of the composite will increase (Richardson and Lokensgard, 1997).

Fiber orientation also has a great effect on the properties of the composite. Figure 4 illustrates different types of composites based on the fiber orientation: If all the fibers are in one direction, the composite is called unidirectional (a); if the composite has the fibers oriented in all directions, it has randomly oriented fibers (b); if they are in two perpendicular directions, it is called orthogonal or bidirectional (c); and in layers oriented in different directions (d).

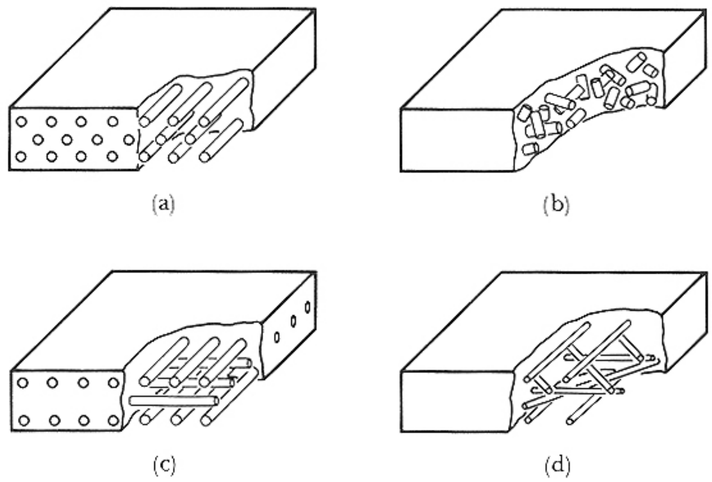


Figure 4: Different fiber orientations within the composite: a) Unidirectional, b) random, c) bidirectional, and d) in multiple directions for different planes (Askeland, 1984).

The composite response with regards to fiber orientation depend on the direction of loading. As seen in figure 5, the composite response differs as the load is applied in different directions with respect to the fiber orientation. The unidirectional composite will have the greatest strength of all composites with a load aligned to the fibers. In other directions its strengths will decrease quite considerably. For the bi-directional composite, the highest strength will be lower, but it will occur in two directions. In this manner, as the direction of the fibers becomes more evenly distributed throughout the composite, the highest strength will be diminished, but the properties will become more uniform in all loading orientations.

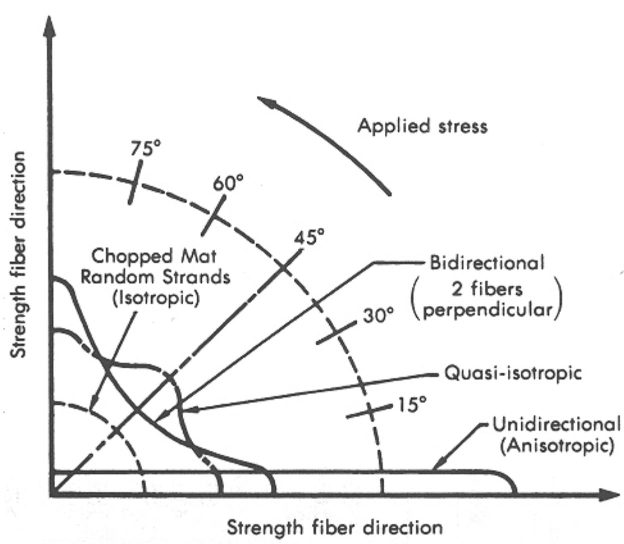


Figure 5: Dependence of properties based on fiber and loading stress orientations (Richardson and Lokensgard, 1997).

The most common type of composites are polymer matrix composites. However, polymer matrix composites have some disadvantages:

-The polymer matrix is relatively weak which affects the final properties of the composite

-Polymers can only be used in relatively low temperature ranges, else they tend to burn and degrade

-Polymers often degrade quickly in an outdoor environment

-Polymers dissipate heat poorly

-Polymers have high coefficients of thermal expansion

Because of these and other limitations, interest has risen in fiber reinforced composites, but with metal matrices. In this manner, the metal matrices provide improved mechanical properties and broader temperature ranges of application. Figure 6 shows the comparative properties of some composite materials with respect to temperature and composition. It can be seen in this figure that aluminum metal matrix composites are on the leading edge with respect to specific strength at temperatures around 800^{o}F.

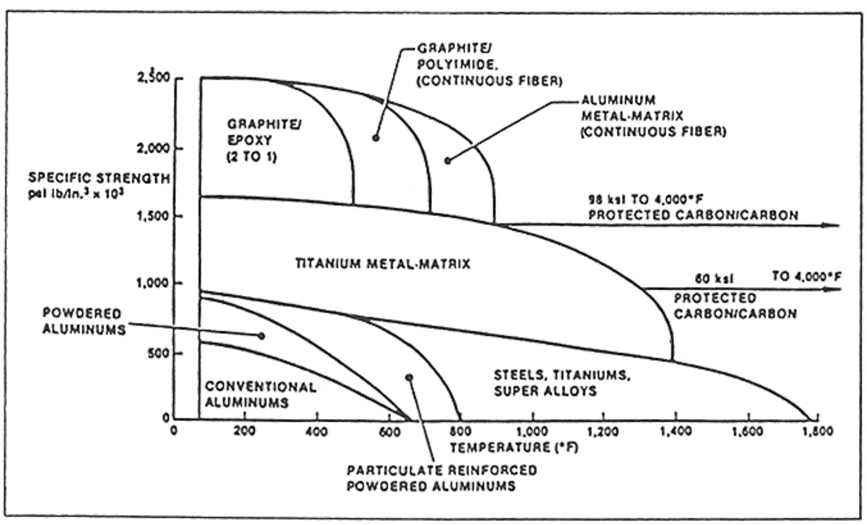


Figure 6: Materials properties at elevated temperatures based on their composition (Stong, 1989).

Matrix Materials

The properties of the composite depend to a great extent on the combination of the properties of the matrix and the fibers. Table 1 shows selected properties of various types of matrix materials. In this table it is possible to see some basic differences between polymer matrices and metallic matrices: The density of metallic matrices is higher, which requiressuperior properties in other areas to justify their use. The metallic matrices do have, in general, higher strengths and lower thermal expansion coefficients. This last property is of particular interest in composites using ceramic fibers.

Table 1: Properties of Matrix Materials

Materials	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Thermal Expansion ($10^{-6}/^oK$)
Polyesters	1.1-1.4	34.5-103.5	2-4.4	55-100
Epoxy	1.2-1.3	55-130	2.75-4.1	45-65
Poyimide	1.46	120	3.5-4.5	90
Phenolic	1.30	50-55	-	45-110
Al 1100	2.7	86	63	25
Al 6061	2.7	136	70	25
Al-7Si	2.7	120	72	25
Ti-6Al-9V	4.5	1034	96	8.5
Compiled from Agarwal and Broutman, 1990; Askeland, 1984; and Riley and Zachary, 1989.				

Fiber Reinforcements

Fiber reinforced metal matrix composites have fibers that are continuous or discontinuous, and they are typically circular and vary in diameter from 0.1 m to 0.1 mm as indicated by Stefanescu (1993). Fiber loading, which is the fiber content of the composite, usually is in the range of 20 to 80% by volume. Optimal load transfer from the matrix to the fibers occurs when fibers are continuous. This is due to the fact that the ends of the fibers do not exercise 100% stress support leading to what is known as an “end effect” for the fiber. However, the discontinuous fibers usually have an aspect ratio that is high enough to limit the end effect to a very small or even negligible factor. Table 2 shows the properties of various fiber materials.

Table 2: Properties of Fiber Materials

Material	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Thermal Expansion ($10^{-6}/^oK$)
Fibers				
E glass	2.55	3440	72.3	
S glass	2.50	4480	86.8	
Alumina	3.15	2070	172.1	7.0
Graphite (High Strength)	1.50	2760	275.4	

Graphite (High Modulus)	1.50	1860	530.2	
Boron	2.36	3450	378.7	
SiC	4.09	2070	482.0	
Kevlar	1.44	3620	123.9	
TiC	4.90	1540	450	
Whiskers				
Alumina	3.96	20,690	426.9	
SiC	3.18	20,690	482.0	3.4
Graphite	1.66	20,690	702.3	
Compiled from Askeland, 1984 and Stefanescu, 1993.				

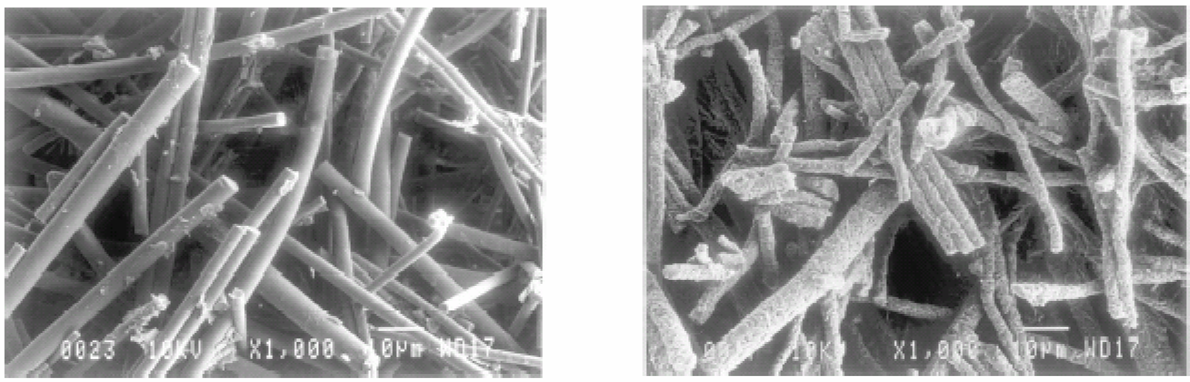
While organic fibers have very good strength to weight properties, they tend to react with the aluminum at processing temperatures damaging the fibers and significantly diminishing their properties. Because of this, organic fibers are not typically used as reinforcement in aluminum and other metals. Ceramic materials are more prevalent in this application.

Fiber-Matrix Bonding

Fiber-matrix bonding is a key factor in the effective transmission of load from the matrix to the fiber. It is essential that this bond is strong for the composite to develop the desired properties. Otherwise, on the onset of stress, the fibers could potentially slide within the matrix, and thus not carry any of the load. The result of this would be that the matrix, now effectively reduced in cross sectional area due to the volume occupied by the ineffective fibers, has to support the entire load. As it was not designed to do so, it will fail.

In order to obtain proper bonding, wetting of the fiber by the matrix material is essential. One method to obtain this wetting consists of subjecting the fiber within the liquid matrix to very high pressures produced by the squeeze casting process. In this manner wetting is accomplished. However, as will be seen later, squeeze casting has limitations so not all composites can be produced at these high pressures. Other methods are necessary. External bonding agents have been explored as fiber coatings. However, results have not been fully satisfactory.

Another method to diminish the pullout potential of fibers from the matrix consists of bonding the fibers together, in a manner similar to a net. Then, there is a mechanical restriction to fiber sliding as the matrix material is restricted due to the bonds between the fiber strands. Peng *et al.* (2001), have bonded alumina fibers in preforms together. They have used two different methods: The first method consisted in sintering the fibers together, with the results illustrated in figure 7. With this approach, there was substantial degradation of the fibers due to grain growth which reduced fiber strength. In the second method a series of binders based on phosphoric acid solutions with and without aluminum hydroxide were used, with the intent of forming an aluminum phosphate binder to bind the fibers together. When the phosphoric acid solution was used by itself it damaged and weakened the fibers due to chemical attack, while the mixture with aluminum hydroxide improved the properties of the preform.



(a) (b)

Figure 7: Microstructure of the alumina preform as received (a) and after sintering at 1650^{o}C for 2 hrs (b) (Peng *et al,* 2001).

Fiber Placement

The most common method to apply the reinforcement in the desired location has been with the use of fiber preforms. Essentially, a fiber preform is similar to a sponge made of the fibers that will go into the composite. This "sponge" is then placed in a mold in the location where the fiber reinforcement is desired. After this, infiltration can take place. The preform also provides for the proper fiber orientation, volume fraction, and distribution in the composite. The typical orientation of fibers in the preform is random, as can be seen in figure 7. The main challenge to the use of preforms is the high pressures currently used to infiltrate the metal. These high pressures can brake the preform.

Other methods of fiber placement have been attempted. Neussl and Sahm (2001) placed fibers by using a variation of the investment casting process. Essentially they coated the fibers with investment casting wax, then placed them in the wax injection mold. As the wax pattern then formed the mold cavity, the fibers ended in the desired location in the mold. This method also had the advantage of being able to use continuous fibers oriented in the loading direction.

No reports were found for the use of dispersion of the fiber reinforcement in molten metal followed by casting. This is a technique commonly used for particle reinforced metal matrix composites. As an explanation the author believes that at the high fiber loading desired, the reology of the metal/fiber mixture would make it very difficult to process.

Metal Infiltration

In order to get the metal to surround the fibers the most effective method has been to infiltrate liquid metal around the fibers with the use of pressure. The basic format is shown in figure 8. Several variations to the process have been developed.

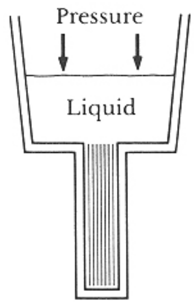


Figure 8: Schematic representation of metal infiltration into the fibers (Askeland, 1984)

Infiltration using squeeze casting is accomplished by using a plunger type arrangement to push the liquid metal into the fibers. Squeeze casting has been the most effective method as it easily applies very high forces to the metal while it forces it into the fiber preform structure. Since the squeeze casting process, when used on aluminum alloys without reinforcements, already employs high forces in the production of components, there is little need to strengthen the dies for use with composites. Disadvantages include preform breakage and the limited geometries that can be generated under the squeeze casting process. Figure 9 illustrates the squeeze casting process.

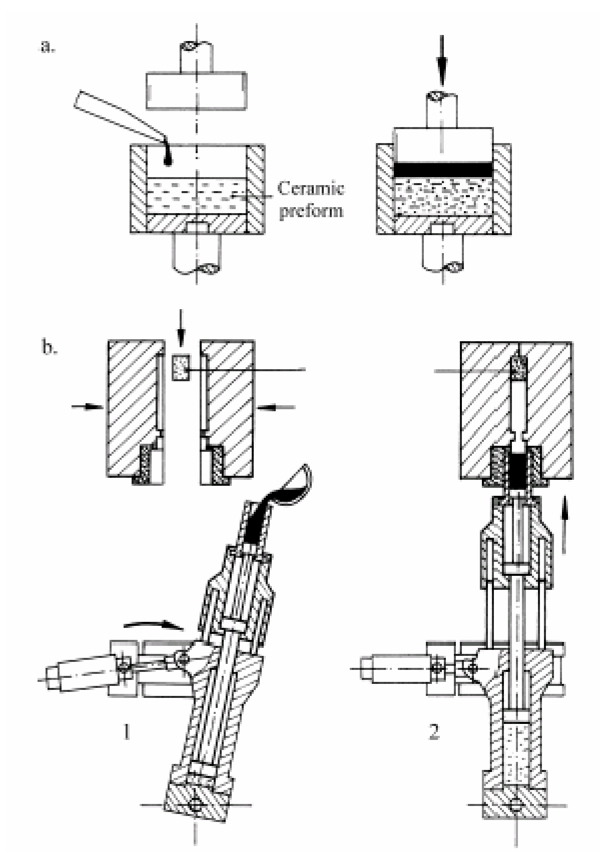


Figure 9: Schematic of the direct (a) and indirect (b) squeeze casting processes (Kaczmar, *et al.,* 2000).

Lim and Clegg (1997) have developed a variation of this method. This new method consists of applying very high forces for infiltration but to investment casting molds. The investment casting process lends itself very readily to the production of very complex geometries. However, as the molds produced in investment casting consist of a simple ceramic shell, they are not strong enough to support the forces required for infiltration. This problem has been overcome by backing the ceramic shell. The infiltration pressure was achieved by using a ram plunger on the sprue of the mold. Figure 10 illustrates this arrangement.

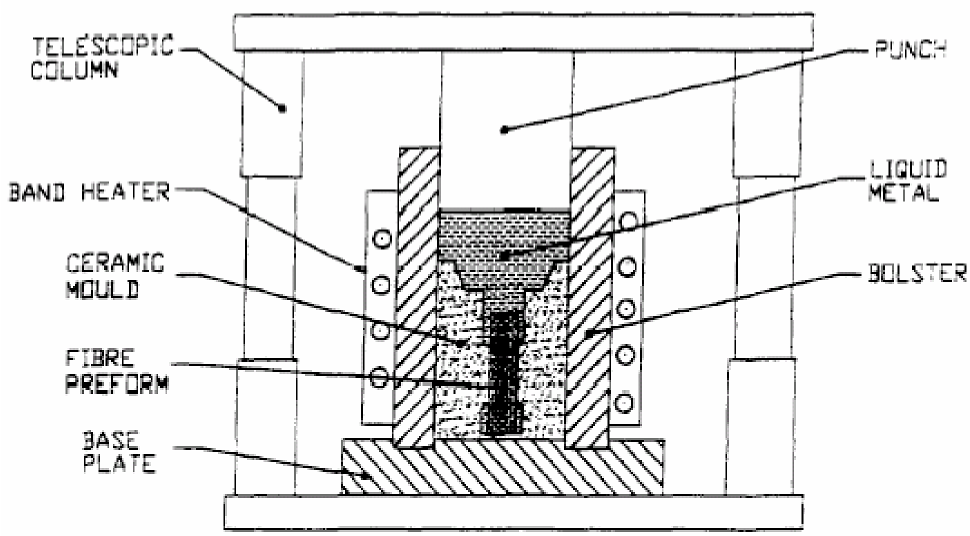


Figure 10: Infiltration arrangement used by Lim and Clegg (1997).

Other work has been done that indicates that infiltration may be achieved at lower pressures. Neussl and Sahm have reported successful infiltration at lower pressures (1 MPa) that were attained by the application of external air pressure on backed investment casting molds. This would allow use of the investment casting process with less modification than the method used by Lim and Clegg, which would allow for easier implementation of production. Material performance benefits have been reported by Lim and

Clegg (1997) due to the microstructural benefits after the application of external pressure to aluminum castings. In addition, the reinforcement seems to promote the formation of a smaller DAS in the grain structure than the conventional Investment Casting process, leading to superior matrix material properties.

These infiltration techniques seem to be the most effective to date.

Alloys

There is conflicting information in this area. While some researchers have indicated that they achieve substantially superior properties by producing fiber reinforced composites with common aluminum alloys, others report marginal improvements. Neussl and Sahm (2001) indicated experimenting with many commercial alloys with no success, which led them to develop a new alloy. Based on the results reported by several researchers and compiled in Table 3, it is difficult to clearly take sides. More than likely, an interaction of the infiltration method/specific fiber used/specific alloy used may be responsible for the wide variations in effectiveness of the reinforcement. It is possible that the low infiltration pressures used by Neussl and Sahm did not provide adequate bonding with conventional alloys, but their new alloy may have bonded better with the reinforcement at these low pressures.

Table 3: Comparative Properties of Fiber Reinforced Aluminum Alloys

Researcher	Alloy	Properties Unreinforced		Fiber	Properties Reinforced		
		UTS (MPa)	E (GPa)		UTS (MPa)	E (GPa)	
Lim and Clegg (Hybrid Method)	Al+7% Si, Similar to BS1490 LM25	185	71	10% Alumina	195	77	
Lim and Clegg (Squeeze)	Same	230	80	Same	245	84	
Neussl and Sahm	Al+6% Zn, 1% Mg, 1% Ag	350	75	50% Alumina	900	135	Unidirectional, Parallel Stress
Neussl and Sahm	Same	Same	Same	Same	200	80	Unidirectional, Perpendicular stress
Kaczmar and Kainer	6061	290	Not Reported	10% Alumina	340	Not Reported	
Kaczmar and Kainer	Same	Same	Not Reported	15% Alumina	340	Not Reported	
Kaczmar and Kainer	Same	Same	Not Reported	20% Alumina	400	Not Reported	
Kaczmar and Kainer	Same	Same	Not Reported	30% Alumina	430	Not Reported	

Machining

Little work has been done with fiber reinforced metal matrix composites. The results are similar to those when machining other fiber composites: Surface and subsurface damage, fiber pullout, and high rates of tool wear. The damage to the material is of particular concern as stresses are often greatest in the surfaces that have been damaged, greatly reducing their effective strength due to the formation of larger flaws at the high stress areas.

The high rates of tool wear simply make the machining of fiber reinforced metal matrix composites more expensive due to lower production rates and higher tooling costs.

Recyclability

The quantity of metal matrix composites produced, both particle and fiber reinforced, is quite small. However, as more metal is recycled, it is expected that the reinforcements in these materials will cause difficulties during the reclamation process as their use becomes more commonplace.

Conclusion

Fiber reinforced metal matrix composites are not yet widely used due to the challenges presented to their commercialization, mainly in the processing costs. As new processing methods get developed, and improvements in fiber/matrix bonding are attained, these materials will have a place in the future for components that require more resistance to the environment, higher operating temperatures, and higher strength than those possible by polymer matrix composites. Based on current research, the future of these materials lies in the ability to economically produce desired shapes by pressure infiltration systems, with the need for improvement in fiber/matrix bonding and perhaps significant alloy development.

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