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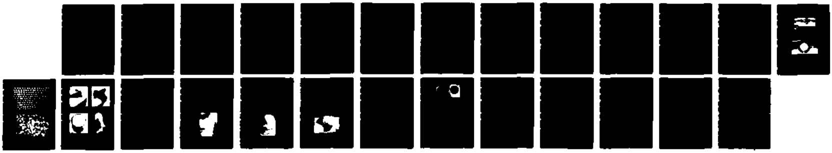

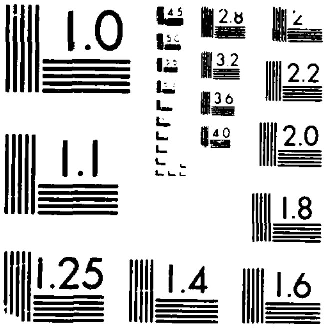

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DRILLING METAL MATRIX COMPOSITES

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MATERIALS EXPLOITATION DIVISION

January 1988

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ABSTRACT

Polycrystalline diamond (PCD) tipped twist and spade drills, diamond plated twist and core drills, and the abrasive waterjet hole cutting process were evaluated for drilling aluminum metal matrix composites reinforced with SiC fibers or particulates. The diamond tipped twist drills outperformed all other drills. Core drills were found to be viable alternatives for the production of larger holes in high volume fraction composites. Plated twist drills were viable alternatives for low volume fraction particulate-reinforced composites. Spade drills failed due to low edge strength. Abrasive waterjet hole cutting was successful for rough, large diameter hole cutting. Recommended drilling parameters are listed for all of the above techniques.

The failure of diamond coated drills used on metal matrix composites was found to have been due to diamond glazing by the hard and abrasive reinforcement material, and loading by the soft metallic matrix. It was determined that the machinability/cutting rate of metal matrix composites can be predicted by using the rule of mixtures and machinability data for the individual components of a composite. High volume fraction reinforcement composites were found to necessitate techniques and tooling similar to those used for diamond grinding. In contrast, low volume fraction reinforcement composites required tool geometries similar to those used for workpiece materials which plastically deform and readily form chips.

INTRODUCTION

Previous experience has shown that conventional cutting tool materials and geometries are not satisfactory for machining metal matrix composites (MMC).[1] Of primary concerns are shortened tool life and damage to the workpiece. The primary reasons for the short tool life are the hardness and abrasiveness of the reinforcing phase. Damage to the work material is also closely related to the reinforcing phase. For example, delamination near the tool exit side of a fiber-reinforced composite can result when excessive cutting forces are required whenever dulled tools are used. Figure 1 shows a severe case of delamination and petalling caused by excessive drill wear and inadequate part fixturing. Figure 2 is a radiograph which shows the extent of lateral fiber damage around an improperly drilled hole.

Diamond tools are used almost exclusively in the traditional machining processes for composites containing more than 25 volume percent ceramic reinforcement. For 25 v/o SiC/Al, a 25% increase in total machining time was needed compared to the same thickness of standard 6061-T6 aluminum alloy. This increases to 300% for 40 v/o SiC_p/Al composites.[2] Other investigators[3] have shown similar results and have estimated fourfold increases in total machining costs for metal matrix composites.

Nontraditional drilling/hole cutting methods such as rotary ultrasonic drilling, laser, and ram electrical discharge machining (EDM) have been attempted on various types of metal matrix composites. The EDM process was found to provide close dimensional control[4] while laser drilling achieved high material removal rates, even though subsequent machining operations were required to produce acceptable surface finishes.[5] These processes, however, are expensive and are often limited by workpiece thickness.

Methods for drilling SiC fiber- and particulate-reinforced aluminum MMC are presented in this paper. Diamond plated core drills, diamond plated twist drills, and polycrystalline diamond tipped twist and spade drills are evaluated, as well as the abrasive waterjet hole cutting process. Results of drilling experiments, to include mechanisms of tool wear and recommended drilling methods, are also presented and are believed to be applicable to many material systems composed of a hard ceramic reinforcing phase in a ductile metallic matrix.

EXPERIMENTAL

Fiber- and particulate-reinforced MMC were used in this investigation. The fiber-reinforced material, produced by AVCO Specialty Materials Division, consisted

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1. DANIEL, W. K., MARIS, J. L., and VAN FICLEN, R. C. *Aluminum Metal Matrix Concepts for Missile Airframes.* Vought Missiles and Advanced Programs Division of LTV Aerospace and Defense Co., Contract F33615-80-3244, Final Report, Air Force Wright Aeronautical Laboratory, Wright-Patterson Air Force Base, OH, AFWAL TR 84-3065, September 1984.
2. SCHOUTENS, J. E. *Discontinuous Silicon Carbide Reinforced Aluminum Metal Matrix Composites Data Review.* MMCIAC No. 461, MMCIAC/Kaman Tempo, Santa Barbara, CA, December 1984.
3. VAN DEN BERGH, M. R. *DWAℓ 20® Status: Machinability, Hardware Examples.* Proceedings, Sixth Annual Discontinuous Reinforced Aluminum Composites Working Group Meeting, Park City, UT, January 4-6, 1984. Published by MMCIAC/Kaman Tempo, Santa Barbara, CA, April 1984.
4. MILLER, M. F., and SCHAEFER, W. H. *Development of Improved Metal - Matrix Fabrication Techniques.* Convair Aerospace Division of General Dynamics Corporation, Contract F33615-70-C-1460, Final Report, Air Force Materials Laboratory, Wright-Patterson Air Force Base, OH, AFML TR 71-181, July 1971 (AD-890605).
5. HANLEY, F., and HARDAGE, J. T. *Manufacturing Methods for Machining Processes for High Modulus Composite Materials, Volume 1, Composite Machining Handbook - Boron.* Convair Aerospace Division of General Dynamics Corporation, Contract F33615-72-C-1504, Final Report, Air Force Materials Laboratory, Wright-Patterson Air Force Base, OH, AFML TR 73-124, Vol. 1, May 1973 (AD-766332).

of 45 v/o unidirectional SCS-2 SiC fibers in a 6061-T4 aluminum matrix. The particulate-reinforced material, produced by DWA, contained 30 v/o SiC in a 7091-T6 aluminum matrix. The thicknesses of the fiber- and particulate-reinforced composites were 0.375" and 0.500", respectively. Photomicrographs of each workpiece material are shown in Figure 3.

Electroplated diamond core drills, diamond plated twist drills, polycrystalline diamond (PCD) tipped twist and spade drills, and standard carbide twist drills were used. All drills were 0.50" in diameter. Photographs of each drill type are shown in Figure 4. It should be noted that both 0° negative and 18° positive rake angles were used on the PCD tipped twist drills.

The test apparatus for conventional drilling consisted of a drill press with adjustable spindle speed. Cutting forces and torques about the spindle axis were monitored with a dynamometer attached to the worktable. A dial indicator was used to measure the depth of cut into the workpiece as a function of time for all experiments. Drilling parameters for representative test runs are shown in Table 1. All thrust force values were kept constant within +/- 20 lbf except where noted.

Table 1. DRILLING PARAMETERS

Drill Hole No.	Drill Type	Material	Tool Condition	Spindle Speed (rmp)	Thrust Force (lbf)	Coolant
1.	Core	SiC_f/Al	Dressed	1115	187.5	Yes
2.	"	"	Dressed	660	"	"
3.	"	"	Dressed	325	"	"
4.	"	"	New	"	"	"
5.	"	"	Dressed	"	"	"
6.	"	"	Dressed	"	375	"
7.	Diamond Plated	"	New	"	187.5	
8.	"	"	"	"	375	
9.	"	"	"	"	187.5	[illegible]
10.	"	"	"	"	375	[illegible]
11.	"	"	"	"	375 Intermittent	[illegible]
12.	Diamond Tipped (Neg.) Twist	"	"	"	187.5	[illegible]
13.	Diamond Tipped (Pos.) Twist	"	"	"	187.5	
14.	Diamond Tipped Spade	"	"	"	375	
15.	Carbide	SiC_p/Al	"	"	[illegible]	
16.	Diamond Plated	"	"	"	[illegible]	
17.	Diamond Tipped (Neg.)	"	"	"	[illegible]	
18.	Core	"	"		[illegible] Intermittent	[illegible]
19.	0.75" Core	SiC	"		[illegible]	[illegible]
20.	"	6061-T6 Al	"	"		
21.	"	SiC_f/Al	"	"		

Abrasive waterjet hole cutting was performed on a Flow Systems PASER abrasive waterjet cutting system using a model 9X intensifier pump. Cutting parameters are shown in Table 2.

Table 2. ABRASIVE WATERJET HOLE CUTTING PARAMETERS

	SiC_f/Al
Cutting Speed (ipm)	1
Pierce Time (sec)	3
Jet Pressure (ksi)	30
Orifice Diameter (in.)	0.018
Nozzle Diameter (in.)	0.062
Abrasive	No. 60 Mesh Garnet
Abrasive Flow Rate (lb/min)	1.25
Standoff Distance (in.)	0.100

RESULTS

The effect of spindle speed on core drill performance was determined (holes 1 to 3). Of the three spindle speeds evaluated, 1115, 660, and 325 rpm no significant difference in penetration rate was observed. However, the drill used at 1115 rpm failed after penetrating approximately 0.100" into the workpiece. Failure was attributed to tool loading caused by insufficient flushing of chips at high rpms.

The effectiveness of dressing worn core drills was evaluated. Figure 5 shows cutting rate data for hole 4 which was drilled with a new tool, and hole 5 which was drilled under the same conditions with the same tool after redressing with a SiC dressing stick. Dressing did restore the initial cutting performance of the worn drill. Cutting rates for both the new and the dressed drills declined significantly after only 0.100" depth of cut. However, the rate of decline in cutting performance for the dressed tool was greater than that of the new tool.

Visual inspection of the drills used for holes 1 through 5 indicated that the rapid degradation in penetration rate experienced was a result of glazing and loading of the core drill. Diamond grains were worn flat and the clearance between adjacent diamond grains and between the bond matrix and the cutting face of the tools was reduced. To alleviate the glazing problem, the thrust force of the tool into the workpiece was increased from 187.5 lbf to 375 lbf for hole 6 in an attempt to make the bond matrix act "softer." Cutting rate data for hole 6 was initially about double that of hole 5, but decreased dramatically at approximately 0.200" depth of cut, (see Figure 5).

The rate of change in cutting rate for hole 6 at 0.200" depth of cut was similar to that of hole 5 at its maximum penetration depth, indicating that the same final stage mechanism of tool wear was operative. There was some initial advantage to increasing thrust force, e.g., the maximum depth of cut before the rapid decline in cutting rate was delayed from 0.100" to 0.200". It was felt, however, that increasing thrust force alone was only a partial solution to the tool wear problem, since drills used for workpieces greater than 0.200" in thickness would have to be redressed before a single hole could be completed.

The effect of increased thrust force on the tool into the workpiece was similarly tested for the diamond plated drills (Figure 6, holes 7 and 8), however, no overall improvement was seen.

The effect of proper coolant application was determined to be critical for the diamond plated drills (Figure 6, holes 9 and 10). Drills used without coolant, a water miscible fluid, failed within 20 seconds and exhibited cutting torques 50% lower than those observed when coolant was used.

Improved flushing within the cut area was attempted for the core drills. This was accomplished for hole 11 by manually applying a 375 lbf load on the tool into the workpiece for three to four seconds followed by retraction of the tool and flushing of the cut area for approximately one second. Cutting rate data for hole 11, shown in Figure 5, was initially the same as that of hole 6, drilled with constant tool load, but did not decrease significantly for the depth of cut tested. Also, the cutting torque for hole 11 was 26% higher than that of hole 6. Intermittent flushing of the cut with coolant can therefore be used to control tool loading and delay the onset of the rapid tool wear experienced when machining MMC.

Both the positive and the negative rake diamond tipped twist drills penetrated the SiC_f/Al workpiece within 10 seconds. However, the diamond tipped spade drill chipped and failed within 5 seconds.

Depth of cut versus time to attain that depth of cut is plotted for drills 8, 11, 12, and 14, which are representative of the best conditions for each drill type tested on the SiC_f/Al, in Figure 7. It is clear that the diamond tipped twist drills (1.5 ipm/0.0046 ipr) outperformed the diamond tipped spade drill (failed), diamond plated twist drill (0.047 ipm/0.00015 ipr) and the diamond plated core drill (0.035 ipm/0.0001 ipr). Although the speeds for the diamond plated twist drills were quite similar to those of the diamond core drills, the core drills could be dressed and reused, whereas the diamond plated drills had to be discarded (Figure 8).

Additional holes were drilled with the negative rake diamond tipped twist drill into the SiC_f/Al composite to determine the drills wear rate and durability. Figure 9 is a plot of the number of holes drilled versus the time to complete each hole. Cutting rate data for the diamond tipped drill declined at a rate of 6.25% per inch feed. The wear land on the PCD tipped twist drill after 30 holes is shown in Figure 10.

Cutting performance data for standard carbide twist (hole 15), diamond plated twist (hole 16), diamond tipped twist (hole 17) and diamond core drills (hole 18) are shown in Figure 11 for the 30 v/o SiC particulate reinforced aluminum. Drilling parameters for each tool are shown in Table 1. The carbide twist drill began to cut, but wore out after approximately 20 seconds. The diamond tipped twist drill (2.5 ipm/ 0.0076 ipr) once again outperformed the diamond plated twist drill (0.42 ipm/0.ipm 0.0013 ipr) and the diamond core drill (0.12 ipm/0.0004 ipr). In addition, the diamond coating on the diamond plated twist drill used in producing hole 16 remained intact (Figure 12).

Drilling performance data for holes 8 and 16, both drilled with diamond plated twist drills and the same parameters, show the increased machinability rate of the 30 v/o SiC_p/Al composite over that of the 45 v/o SiC_f/Al composite (Figure 13).

Three 0.75" OD core drills were also used to make holes 19 to 21 in SiC, 6061-T6 Al, and 45 v/o SiC_f/Al workpieces under the constant thrust force conditions shown in Table 1. Drilling performance data for these tests are shown in Figure 14. Cutting rates for the SiC were 0.025 ipm, SiC_f/Al 0.088 ipm and 6061-T6 Al 0.132 ipm. Similar tests could not be conducted for the other drill types because of their inability to cut the SiC monolithic plate.

A photograph of typical abrasive waterjet holes cut in the SiC_f/Al material is shown in Figure 15. Hole quality and dimensional accuracy were found to decrease with increased nozzle wear and cutting speed.

DISCUSSION

Experimental results have shown that the rapid wear of diamond plated drills is primarily due to the onset and degree of glazing. When glazed, diamond grains wear flat and new cutting facets are infrequently exposed. Compounding this problem is loading by aluminum which reduces the clearance between the bond and the workpiece. Loading results in a "harder" acting bond since higher mechanical pressures of drilling are required to break the bond which holds the dull grains to the cutting tool.

Figure 16 is a typical dynamometer recording showing cutting torque versus time for a core drilled hole in SiC_f/Al composites. Figure 17 is a plot of cutting torque versus depth of cut for this hole. The torque values shown in this figure represent the torque required to machine through individual plies of SiC fibers which are the minimum values of the cyclic dynamometer torque recording of Figure 16. As shown in Figure 17, these torque values decline with depth of cut, indicating glazing as an initial mechanism of tool wear. A nominally linear rate of decline in torque values occurs to approximately 0.150" depth of cut and is followed by a more dramatic decline. This change in slope indicated an additional mechanism of tool wear, loading by the aluminum, which increases the degree of glazing beyond that which can be attributed to the machining of SiC plies alone.

In summary, the rapid wear rates for diamond plated drills used to machine MMC are due to a combination of the hard and abrasive reinforcement which results in diamond glazing and the soft metallic matrix which loads the tool and eventually accelerates the rate of tool glazing by preventing dulled cutting facets from being discharged from the tool bond. Low speeds, high feeds, frequent dressing, and proper coolant application are therefore recommended for the drilling of both the fiber- and particulate reinforced composites.

Cutting rate data derived from Figure 14, which shows core drilling results on SiC, 6061-T6 Al, and SiC_f/Al, indicate that the cutting rate of SiC_f/Al can be predicted by the rule of mixtures using machinability/cutting rate data for the two individual components of the composite, SiC and Al. One can assume that this not only applies to SiC_f/Al but to all aluminum matrix composites regardless of matrix and reinforcement composition. The form and distribution of the reinforcement may alter this relation in a secondary manner.

Since the mechanism of material removal for the reinforcement phase is vastly different than that of the matrix material, e.g., brittle fracture versus shear, tools should be selected based on volume fraction reinforcement. High volume fraction reinforcements require techniques and tooling similar to diamond grinding while low volume fraction reinforcement composites require tooling similar to that used for materials which plastically deform and readily form chips.

Figure 13 shows that for the 45 v/o SiC_f/Al the performance of the diamond plated twist drills and the diamond core drills are quite similar. Since significant wear of the plated twist drill prevented its reuse, core drills are considered to be superior to plated twist drills for high volume fraction reinforcement composites. Figure 13, however, also shows that for the 30 v/o SiC_p/Al, diamond plated twist drills significantly outperform diamond core drills. The reduced volume fraction of SiC, the random dispersion of particulate, and the small l/d ratio of the reinforcement are all believed to contribute to the enhanced performance of the diamond plated twist drill on low volume fraction particulate-reinforced materials.

Since the diamond grit size on the plated twist drills is significantly larger than that of the core drills, the plated twist drills can tolerate larger volume fractions of matrix material without loading. However, larger grit sizes also correspond to weaker bond strengths which are a disadvantage when penetration through numerous plies of continuous fiber reinforcement is required.

As hole size increases, the force required to remove a unit volume of chips increases at a faster rate for the plated twist drills than the core drills. In addition, since the diamond coated surface area of twist drills increases faster with drill diameter than that of core drills, the cost difference between core and twist drills decreases with drill size. For example, a 0.125" core drill costs 4 times as much as a diamond plated twist drill of the same size. A 0.750" diameter core drill costs 1.5 times more than a twist drill of equivalent size. Therefore, as hole size increases, core drilling and possibily abrasive waterjet cutting become more viable alternatives for low volume fraction reinforcement composites.

A similar cost/diameter ralationship exists between the core and diamond tipped drills. For example, 0.125" diameter diamond tipped twist drills cost 2.5 times that of the same diameter core drill, whereas 0.750" diameter diamond tipped drills may cost 5 times as much. Although the cost of diamond tipped drills is high, cutting speeds are also high. There may be no other tool capable of producing holes in heavy sections of high volume fraction fiber-reinforced composites. These drills may, however, be proned to chipping if misused, as evidenced by the spade drill results, but may be resharpened if removed from service before wear lands becomes excessively large. However, the cost of regrinding is high. Negative rake diamond tipped drills are recommended over positive rake drills for additional edge strength, especially with high volume fraction fiber-reinforced composites.

Abrasive waterjet hole cutting is a viable rough hole making process for all types of composites. While tooling costs are low, initial capital investment costs are, however, high.

CONCLUSIONS

Drilling speeds/penetration rates for 30 v/o SiC_p/Al and 45 v/o SiC_f/Al composites were 2.5 ipm and 1.5 ipm respectively, for the 0.50" diameter polycrystalline diamond tipped, negative rake, twist drills. The drilling performance of the diamond plated twist drills, diamond core drills, and diamond tipped spade drills is inferior to that of the diamond tipped twist drills, especially for small holes. The initial cost of the tipped twist drills, however, is extremely high.

Diamond core drills are a viable alternative for larger diameter holes in high volume fraction reinforcement composites. Frequent dressing, low speeds, and high feeds are recommended for these drills. However, intermittent flushing of the cut area (e.g., interrupted feed rates) is required for high volume fraction reinforcement composites.

Diamond plated twist drills are a viable alternative for hole drilling low volume fraction particulate reinforced materials. However, they cannot be successfully applied to high volume fraction fiber-reinforced composites. Unlike the other drills tested, plated twist drills may not be resharpened. However, their cost is only 10% that of a diamond tipped drill.

Diamond tipped spade drills are unsuitable for fiber-reinforced composites due to their low edge strength.

Abrasive waterjet hole cutting is viable alternative for rough, large diameter hole making in both particulate and fiber high volume fraction reinforcement composites.

The failure mechanism of any diamond coated drill used to machine metal matrix composites is primarily related to the onset and degree of glazing. When glazed, diamond grains wear flat and new cutting facets are infrequently exposed. Compounding this problem is loading which reduces the clearance between diamond grains and between the bond and the workpiece.

The machinability/cutting rate of any metal matrix composite can be predicted by the rule of mixtures using machinability/cutting rate data for the individual components of a composite.

Figure 1. Delamination of a fiber-reinforced composite which resulted from excessive cutting forces. Dull tool at inset. Mag. 8X

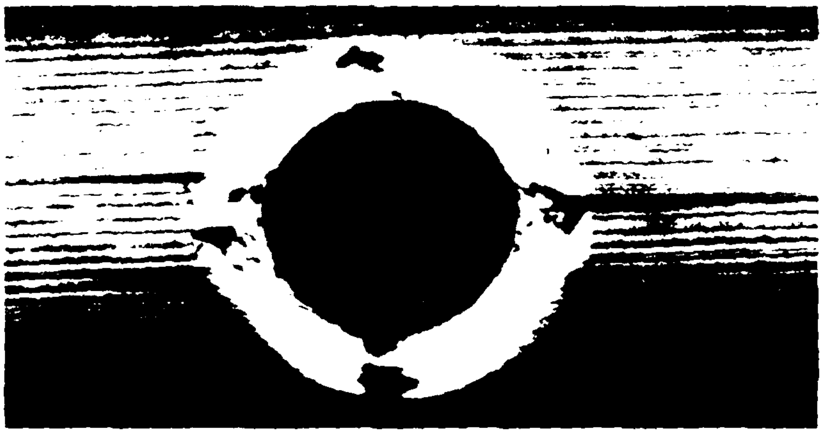
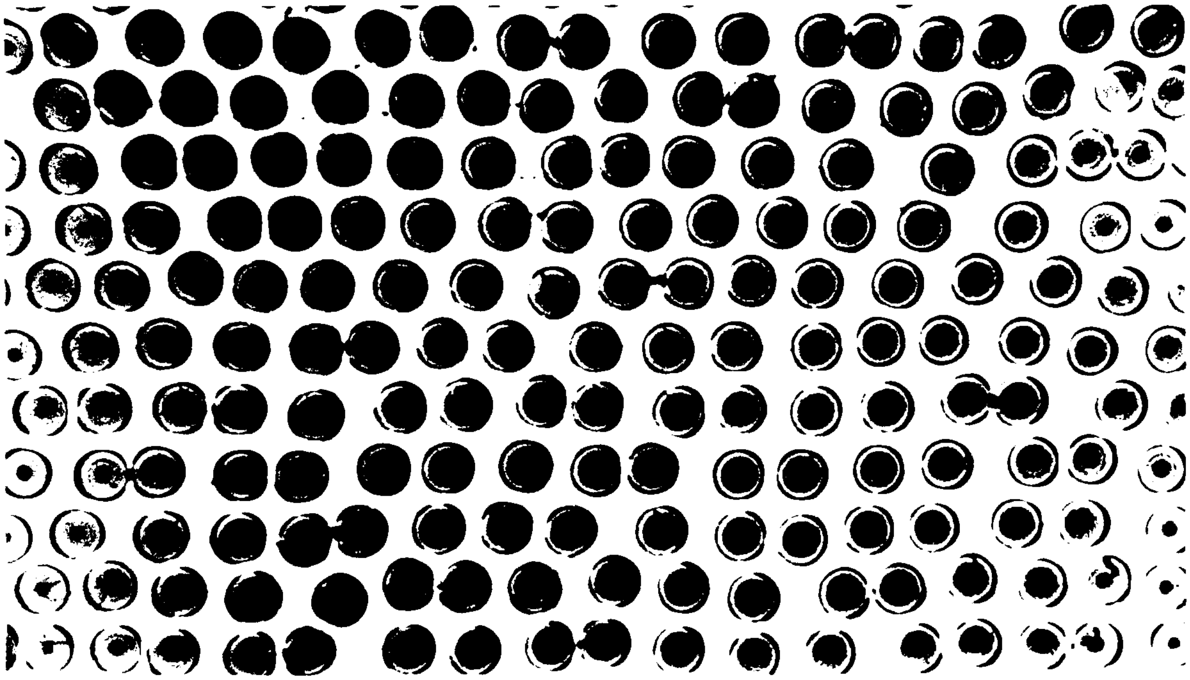
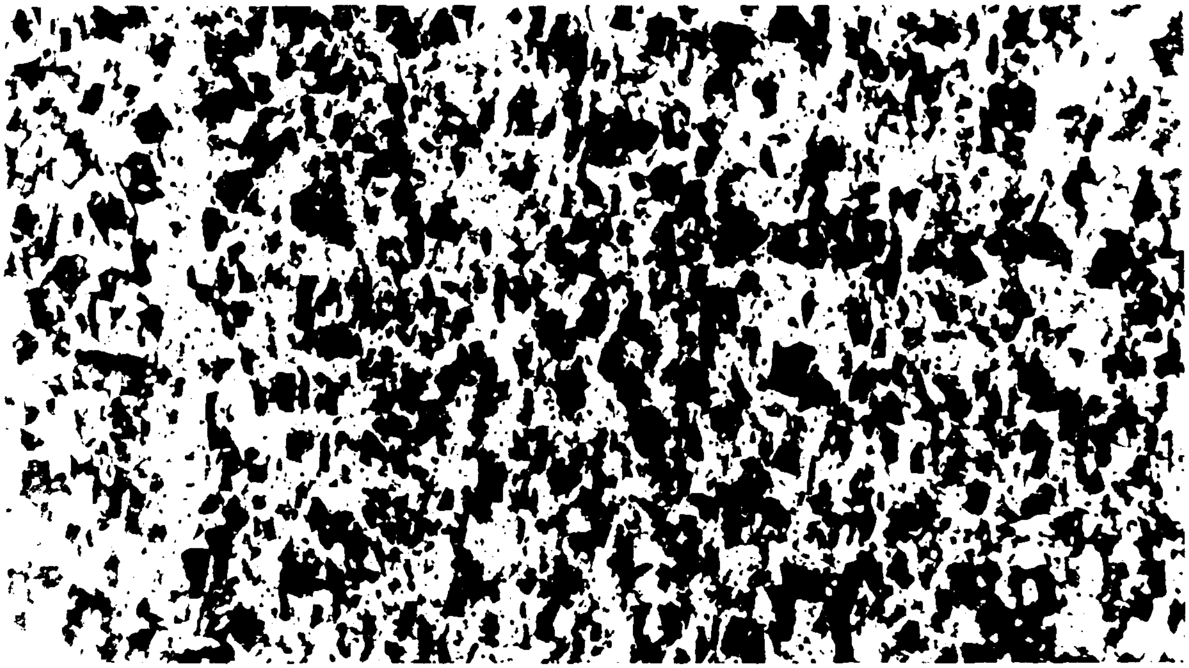


Figure 2. Radiograph of drilled hole in SiC_f/Al composite. Mag. 10X



Fiber Reinforced, Mag. 50X



Particulate Reinforced, Mag. 500X

Figure 3. Photomicrographs of SiC metal matrix composites.

a. [illegible] Tapered Twist Die

b. Diamond Plated Twist Die

c. Diamond Plated Cone Die

d. Diamond [illegible] Shaft Die

[illegible]

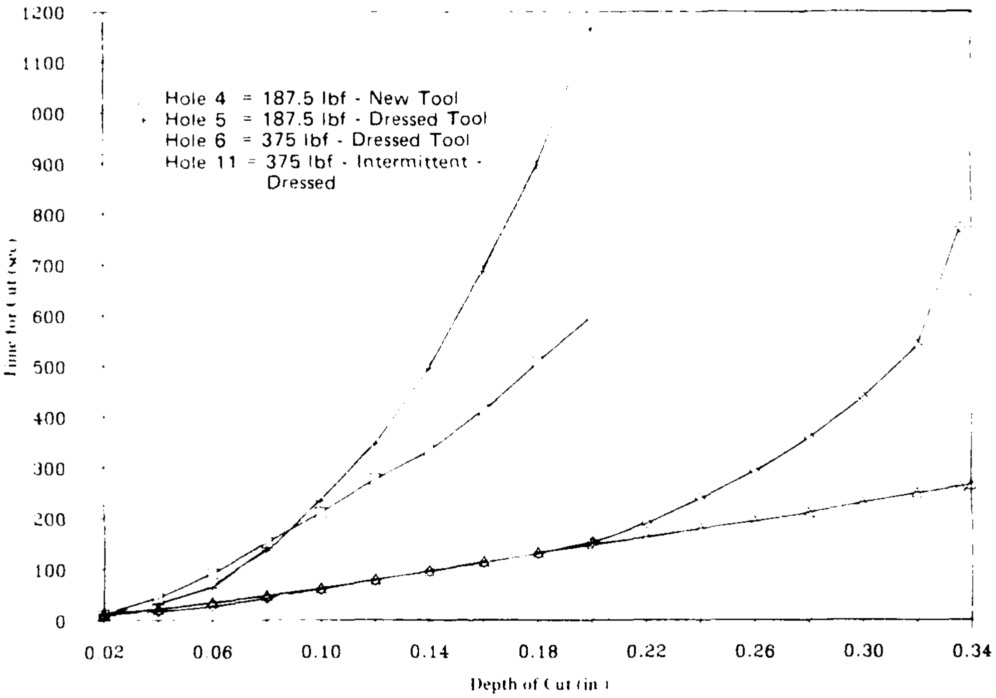


Figure 5. Plot of depth of cut versus time to attain a given depth of cut for four core drilling conditions.

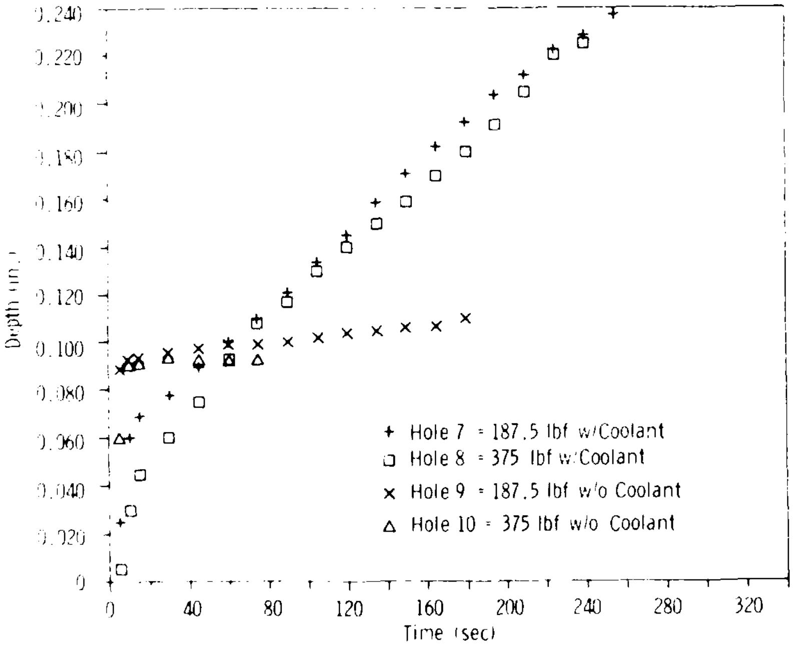


Figure 6. The effect of thrust force and coolant on the performance of the diamond plated twist drills.

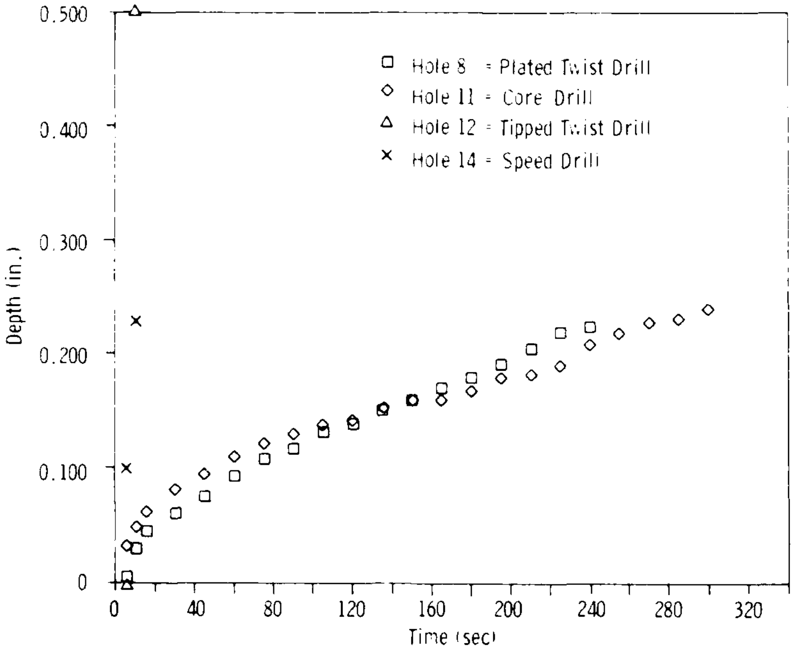


Figure 7. Plot of depth of cut versus time to attain a depth of cut into the SiC_f/Al with the diamond tipped twist and spade drills and the diamond plated core and twist drills.

Figure 8. Diamond plated twist drill after one hole into the SiC_f/Al workpiece. Mag. 5X

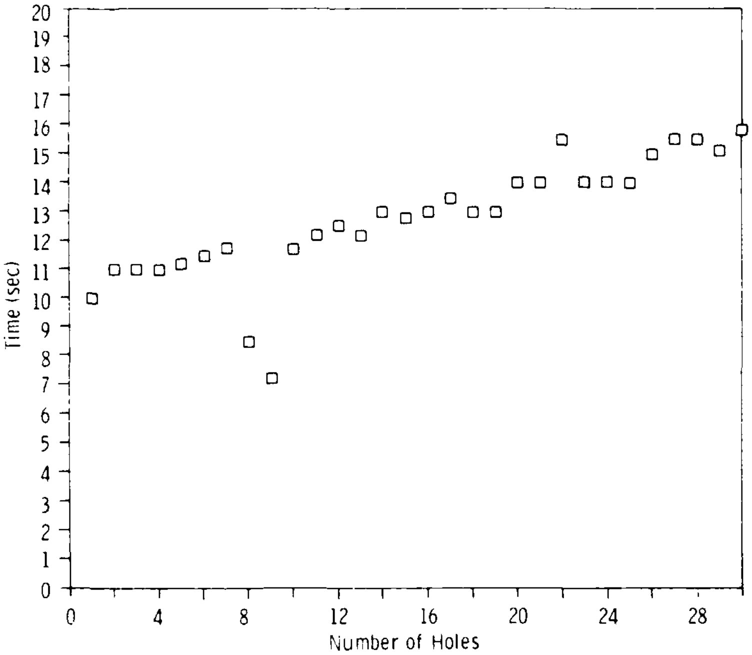


Figure 9. Plot of the time to complete a hole versus number of holes drilled for the PCD tipped twist drill.

Figure 10. Wear land on the PCD tipped twist drill after 30 holes into SiC$_f$/Al workpiece. Mag. 5X

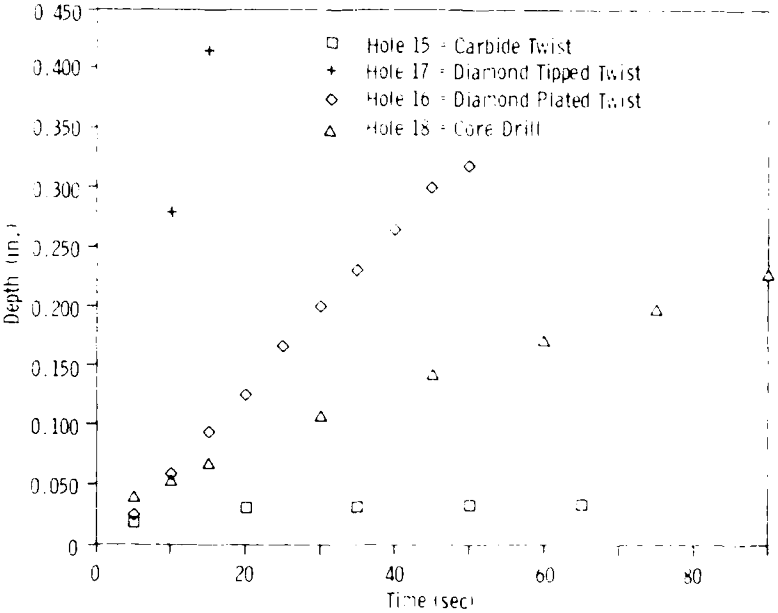


Figure 11. Plot of depth of cut versus milling time for the SiC_p/Al workpiece with core drills and diamond tipped, diamond plated, and carbide twist drills.

Figure 12. Diamond plated twist drill used to make six holes into the SiC_p/Al workpiece. Mag. 5X

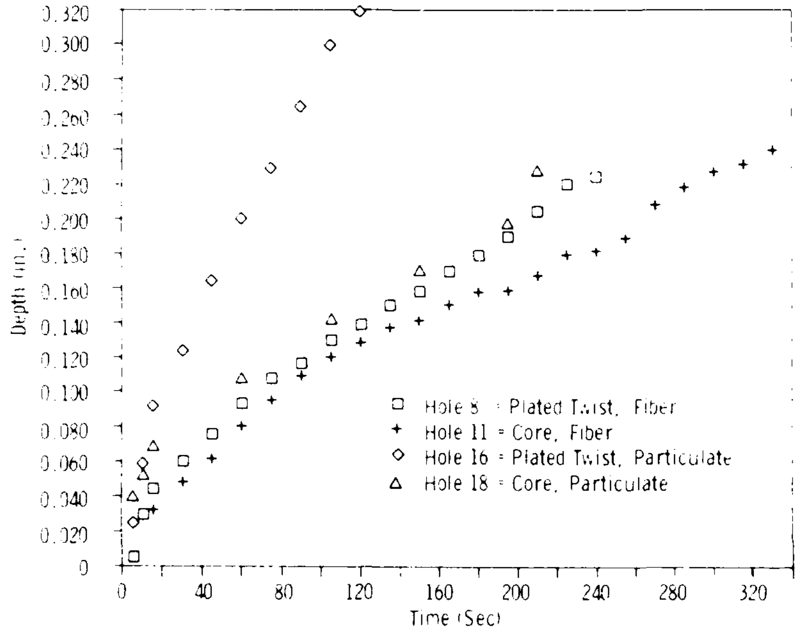


Figure 13. Depth of cut versus time for core drills and diamond plated twist drills used on both the SiC_f/Al and SiC_p/Al workpieces.

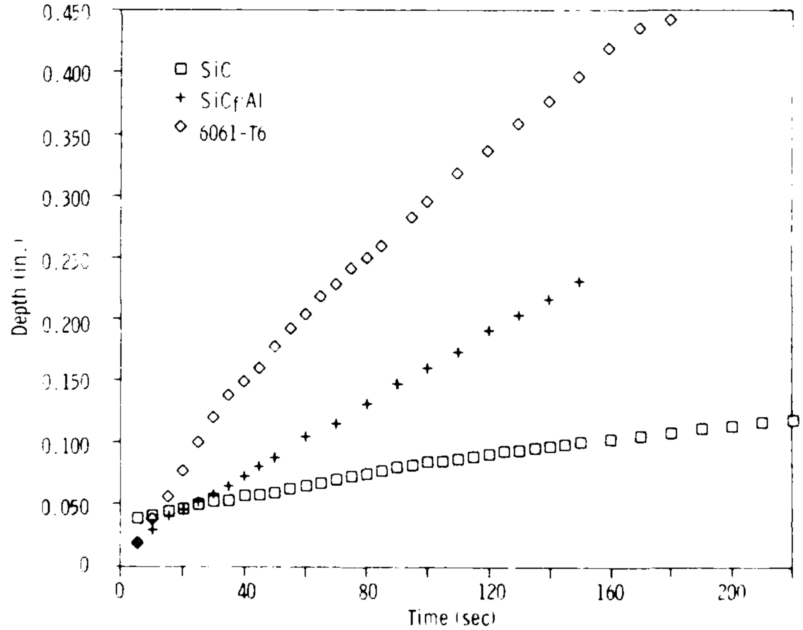


Figure 14. Core drill performance data on SiC, 6061-T6 Al and 45 v/o SiC_f/Al workpieces.

Figure 15. The 0.25" and 0.50" diameter holes cut by the abrasive waterjet process into the SiC_f/Al workpiece.

Figure 16. Dynamometer recording showing torque data. Chart speed 1 mm/sec.

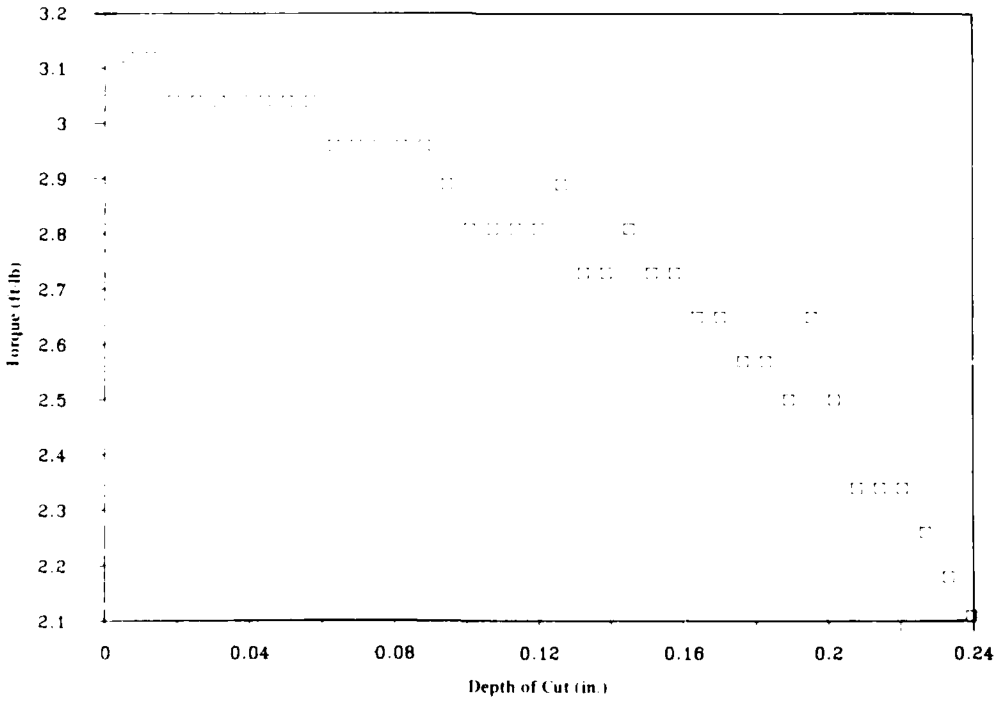


Figure 17. Torque required to machine individual plies of SiC fibers versus depth of cut.

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and Thomas [illegible]

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Polycrystalline diamond [illegible] tipped twist [illegible]
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