GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-25-G01 GTRC/XXXX DATE 2 /22 /85

Project Director: John Berry School/XXX ME

Sponsor: Lockheed - Georgia Company

Type Agreement: Research Agreement dated 2/13/85; P.O. #CB88899, Control #0185717

Award Period: From 2/13/85 To 12/31/85 (Performance) 12/31/85 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 25,758
Funded:	$	$ 25,758

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: A Study of the Machinability of Abrasive Inclusion Containing Alloys

ADMINISTRATIVE DATA

OCA Contact John Schonk x4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

W. R. Britton
Lockheed - Georgia Co.
Marietta, GA 30063

Defense Priority Rating: N/A Military Security Classification: N/A
(or) Company/Industrial Proprietary: *

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor

COMMENTS:

Invoice for advance payment of $6,000 has been sent.
Sponsor has agreed to pay $3,864 for Patent & Data Review Rights
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GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 4-9-87

Project No. E-25-G01

School/~~XXX~~ ME

Includes Subproject No.(s) N/A

Project Director(s) John Berry — GTRC / ~~XXX~~

Sponsor Lockheed - Georgia Company

Title A Study of the Machinability of Abrasive Inclusion Containing Alloys

Effective Completion Date: 12/31/85 (Performance) 12/31/85 (Reports)

Grant/Contract Closeout Actions Remaining:

- [x] None
- [ ] Final Invoice or Final Fiscal Report - Already Submitted.
- [ ] Closing Documents
- [ ] Final Report of Inventions - Already submitted.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

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Angela DuBose
Russ Embry

FORM OCA 69.285

ON THE MACHINING OF ALUMINUM ALLOYS CONTAINING A HIGH VOLUME FRACTION OF ABRASIVE PHASES

Interim report

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August 28, 1985

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INTRODUCTION

The development of new engineering materials is a continuous process driven by both the desire to improve current material systems and the need to find candidate materials for applications too demanding for existing materials. For instance, the aircraft and land vehicle industries will always be looking for new materials that are stronger and lighter so that fuel consumption can be reduced. The development and use of graphite/epoxy composites, extremely stiff and lightweight materials, is one result of these efforts. However, there are a number of emerging material applications where the use of graphite/epoxy composites is inappropriate. The aerospace industries, in particular, require materials that retain their strength at high temperatures and have good thermal and electrical conductivities. These material requirements limit the designer to metallic materials. Thus, research aimed at developing composites with metal matricies is increasing.

Recently, the U. S. Department of Defense has begun a development program to commercialize metal matrix composites (MMC) as a cost effective replacement for the metal alloys currently used in aerospace applications. These composites consist of a metallic matrix such as aluminum or titanium reinforced with high strength, high modulus whiskers or fibers such as boron (B), silicon carbide (SiC), and aluminum oxide (Al_2O_3). MMCs exhibit elastic moduli and strength up to twice that of the matrix material and are expected to increase performance, reduce weight, and reduce life cycle costs of aircraft [1]. One of the most promising MMC systems is the aluminum/silicon carbide

(Al/SiC) system. These composites are produced by a powder metallurgy technique and hence, are nearly isotropic. They can be forged, extruded, rolled, and pressed and are expected to offer designers a relatively low cost material for applications requiring high specific stiffness and strength [2].

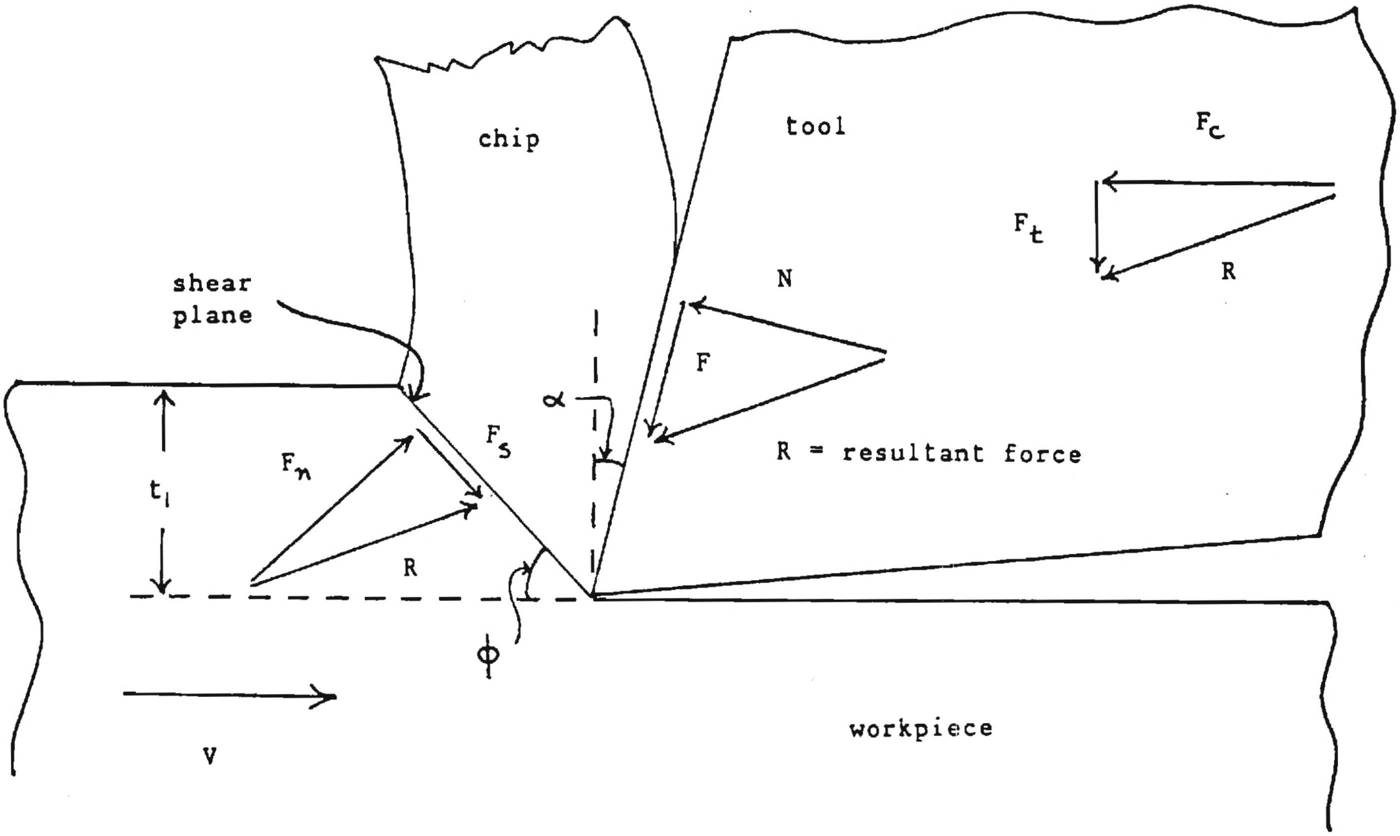
However, silicon carbide is an extremely hard, abrasive material and its use as the strengthening phase in these composites causes tool wear problems during machining operations. In this sense, these composites are similar to white cast irons in that they are notoriously difficult to machine. This is because their microstructures consist basically of a very abrasive phase distributed in a tough matrix. An optimum methodology for machining metal matrix composites has not yet been defined simply because of their very recent development and limited availability. Polycrystalline diamond has recently emerged as the current best tool material due to its high abrasion resistance, but very little is known about the effects of depth of cut, tool geometry, and cutting speed on the cutting process. The goal of this initial investigation is to conduct a basic, two-dimensional cutting operation and to determine the effects of the above-mentioned parameters on tool forces and surface finish. In addition, the effect of lubrication and percent volume fraction of silicon carbide whiskers will be examined. It is hoped that this fundamental investigation will help determine the optimum approach to cutting this class of materials.

EXPERIMENTAL DESIGN

Since the goal of the investigation was to determine the effects of basic machine and tool parameters on the machining of MMCs, it was deemed necessary to perform orthogonal, or two-dimensional cutting whenever possible. The mechanics relationships between cutting forces, shear forces, shear strains, etc. for orthogonal cutting were initially developed in this country by Merchant in 1945 [3]. His analysis remains the most useful technique for examining the fundamental response of the workpiece material to the cutting action of a tool. A diagram of the orthogonal cutting process is given in Figure 1 along with a list of the nomenclature used in this report.

Cutting tests were performed on 2124-T6 aluminum with 15% volume fraction of silicon carbide whiskers (SiC_w), 2124-T6 aluminum with 20% volume fraction SiC_w, and 2024-T351 aluminum. This last material is extremely similar to the 2124 aluminum matrix of the two composites tested. The Brinell hardness of the 2024 aluminum was 140 while the 15% SiC_w composite measured 165 and the 20% SiC_w composite measured 174. Each of the specimens was in plate form. The two composites were 0.25" (6.35 mm) thick and the 2024-T351 specimen was 0.5" (12.7 mm) thick.

Circular disks of each workmaterial were cut out and bolted, along with a backing plate of similar size, to the face plate of a lathe. In order to achieve orthogonal cutting conditions, it was necessary to first cut furrows into these disks in order to generate a series of concentric rings of uncut material. The width of these rings was selected to be 0.1" (2.54 mm) which was the width of cut for all the



Nomenclature

Depth of cut: t_1

Cutting speed: V

Rake angle: α

Shear angle: φ

Measured forces: F_c - cutting force
F_t - thrust force

Tool forces: F - friction force
N - normal force

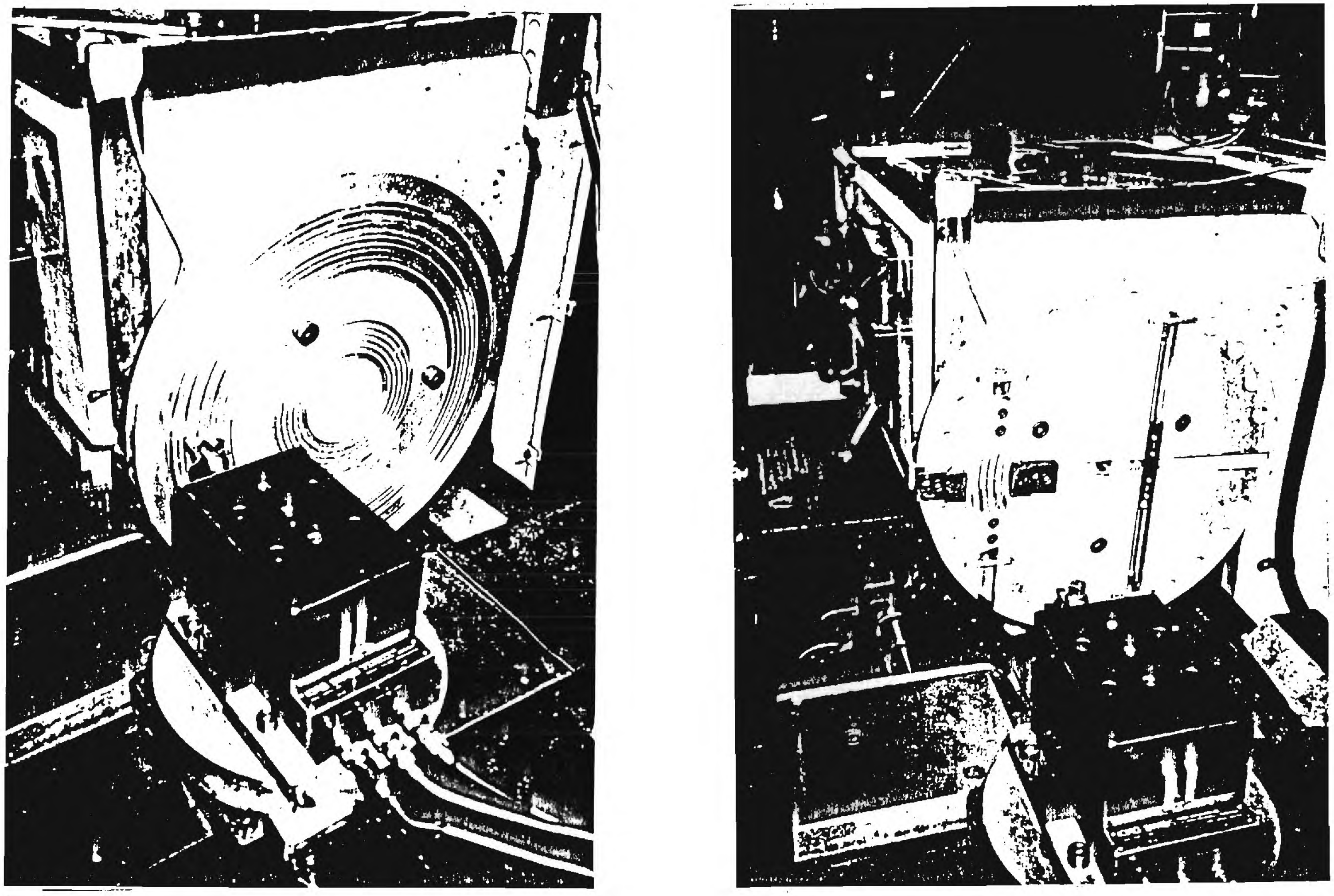
Forces on shear plane: F_s - shear force
F_n - normal force

Figure 1. Diagram of the orthogonal cutting operation and the nomenclature used in this report.

tests. Thus the orthogonal cutting operation in this case, can be visualized as the turning down of short lengths of concentric tubes, each 0.1" thick. A photograph of this set-up is shown in Figure 2a.

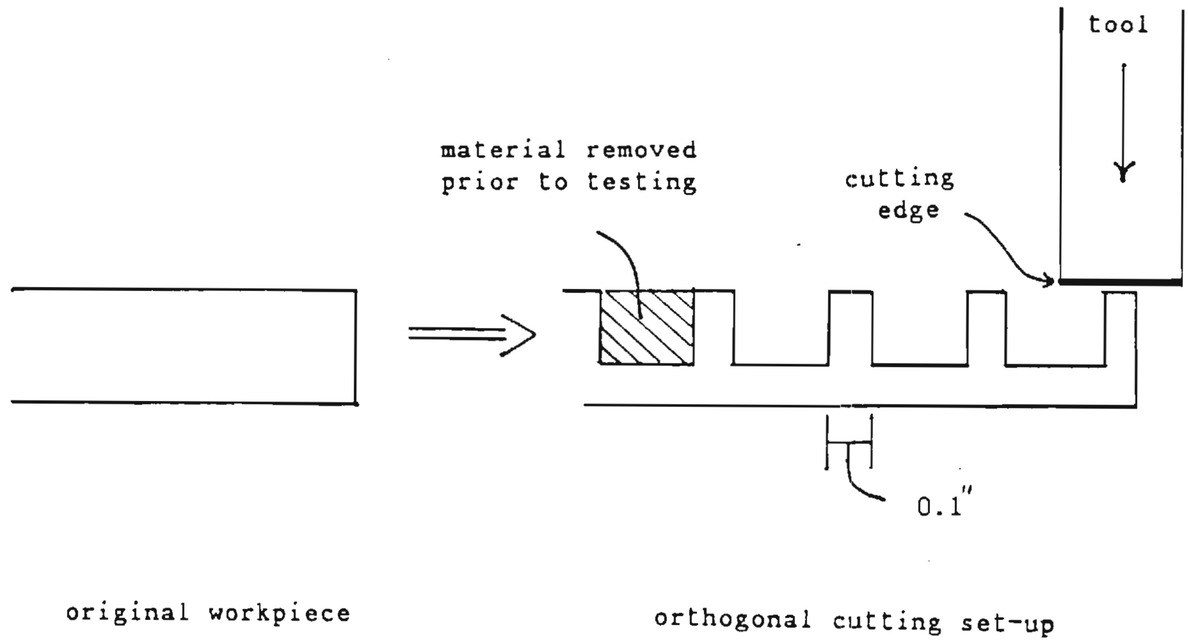
Figure 2b shows a small piece of workmaterial held in a four jaw chuck made specifically for this purpose. The high cost of the two composites under investigation made this set-up attractive for running additional tests. Again, furrows were cut into the workpiece prior to the experiment so that the cutting was carried out on the raised rings of material. This set-up yielded an interrupted cut with the tool being engaged in the workpiece for about one tenth of each revolution of the four jaw chuck.

The 2024-T351 aluminum plate was cut using the set-up shown in Figure 2a which allowed for continuous, orthogonal cutting. The 2124 aluminum reinforced with 15% SiC_w was cut using both set-ups. Thus both continuous and interrupted orthogonal cutting was performed on this workpiece. The 2124 aluminum reinforced with 20% SiC_w was not available in a size large enough to permit orthogonal cutting. Instead, semi-orthogonal cutting was performed on this specimen as well as on the 15% SiC_w reinforced material. In this way, the effect of differing volume fractions of SiC_w could be examined. Semi-orthogonal cutting, as shown in Figure 3, differs from orthogonal cutting in that a corner of the cutting edge of the tool is in contact with the workpiece. This type of cut more closely resembles a typical end milling operation but the mechanics analysis developed by Merchant cannot be applied.



a) b)

Figure 2. Photographs of set-ups for a) continuous orthogonal cutting and b) interrupted orthogonal cutting.



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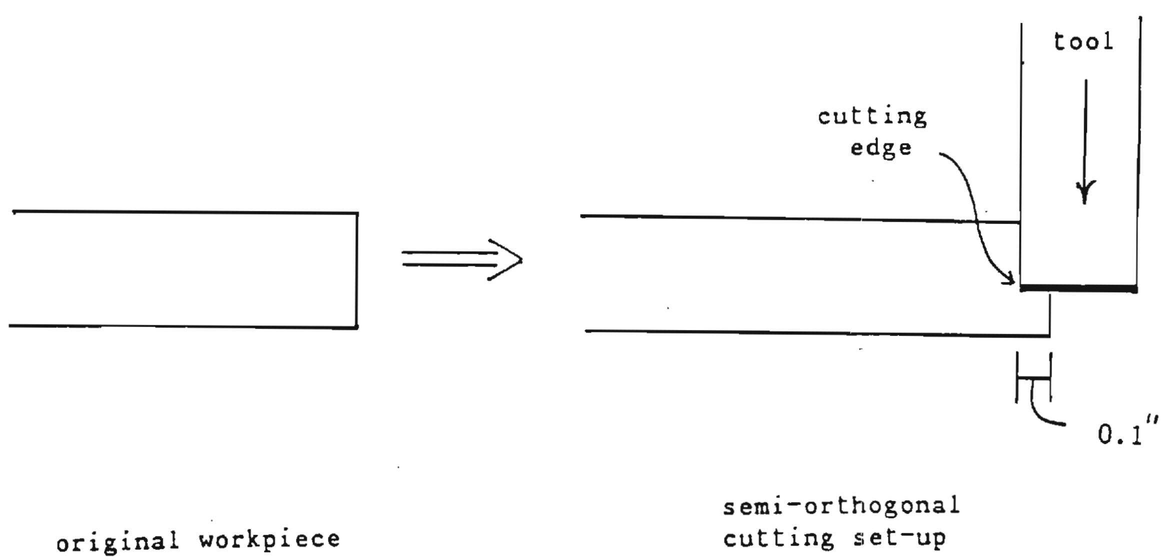


b)

Figure 3. Diagram of a) orthogonal cutting and b) semi-orthogonal cutting.

Brazed carbide tools with a cutting edge width of 0.375" (9.35 mm) were used to machine the two composites while M2 grade high speed steel tools of the same dimensions were used to cut the 2024 aluminum. Carbide cutoff tools with a cutting edge width of 0.3175" (7.94 mm) were used to cut the furrows into the composite specimens. These tools broke after about 750 impacts (revolutions) during the furrowing of the interrupted cut specimens shown in Figure 2b. Furrowing of the 2024 aluminum was done with a high speed steel cutoff tool with a cutting edge width of 0.185" (4.57 mm).

Since the effect of tool geometry was a major emphasis of the investigation, a method of modifying the 0° back rake, 0° end relief angle carbide tools into tools with various back rake angles and a $+5^{\circ}$ end relief angle was needed. In order to preserve the integrity of the top surface of the carbide bits, it was decided to grind various end relief angles onto the tools while also modifying the tool shank or tool holder appropriately. For instance, to produce a tool with a $+5^{\circ}$ back rake and a $+5^{\circ}$ end relief angle, a 10° end relief angle was first ground onto the tool bit and then the tool holder was shimmed up five degrees to give the desired geometry. This method is diagrammed in Figure 4 for each of the four tool geometries used.

All cutting tests were performed on a ten horsepower Springfield lathe with a variable speed control. The tool post was mounted on a Kistler Instrument AG type 9257A piezoelectric dynamometer which was used to measure the two cutting forces. These are the so-called cutting (F_c), and thrust (F_t) forces shown pictured in Figure 1. The force traces were recorded on a Hewlett Packard 7100BM, two channel strip

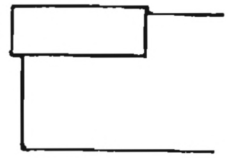
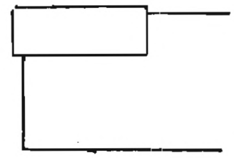
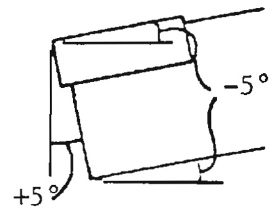
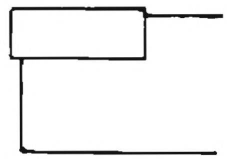
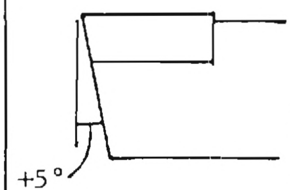
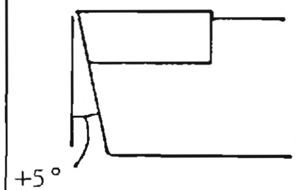
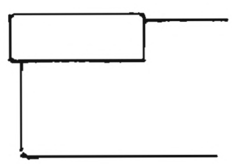
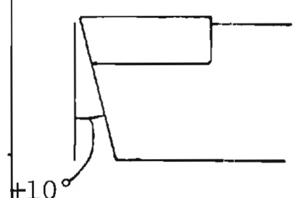
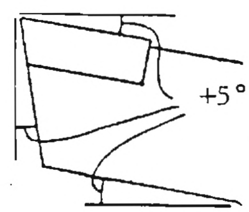
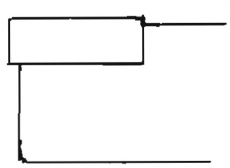
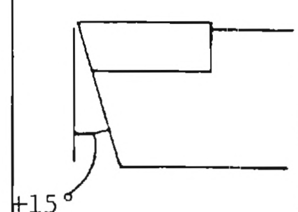
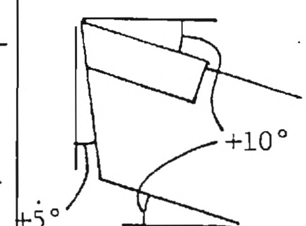
DESIRED TOOL GEOMETRY	INITIAL SHAPE	AFTER GRIND	AFTER SHIM
-5° Back Rake Angle +5° End Relief Angle		 No Grind	 -5° Shim
0° Back Rake Angle +5° End Relief Angle		 5° Grind	 No Shim
+5° Back Rake Angle +5° End Relief Angle		 10° Grind	 +5° Shim
+10° Back Rake Angle +5° End Relief Angle		 15° Grind	 +10° Shim

Figure 4. Method used to achieve desired tool geometries

chart recorder for the continuous cutting tests shown in Figure 2a. A Tektronix 5103 dual beam storage oscilloscope was used to capture the force traces from the interrupted cut tests shown in Figure 2b. Table 1 below lists the range of input variables tested for each of the workpieces.

Table 1. Range of input variables tested for each workpiece

Material	Type of cut	Input variables
2024-T351 Al	Orthogonal	Back rake angle: $+5^\circ, +10^\circ$ End relief angle: $+30^\circ$ Cutting speed: 100*,325,550, 775,1000,1250*,1450* sfpm. Depth of cut: 0.0047,0.0063, 0.0080 inches
2124-T6 Al with 15% SiC_w	Orthogonal	Back rake angle: $-5^\circ, 0^\circ, +5^\circ, +10^\circ$ End relief angle: $+5^\circ$ Cutting speed: 325,550,775, 1000 sfpm. Depth of cut: 0.0047,0.0063, 0.0080 inches
2124-T6 Al with 15% SiC_w	Semi-orthogonal	Back rake angle: $+5^\circ$ End relief angle: $+5^\circ$ Cutting speed: 100*,325,550, 775,1000 sfpm. Depth of cut: 0.0047,0.0063, 0.0080 inches
2124-T6 Al with 20% SiC_w	Semi-orthogonal	Back rake angle: $+5^\circ$ End relief angle: $+5^\circ$ Cutting speed: 100*,325,550, 775,1000 sfpm. Depth of cut: 0.0047,0.0063, 0.0080 inches

* only for depth of cut of 0.0047 inches

Chips were collected from each cut and their thickness was measured where possible. The high speed steel tools were polished in between tests to remove any built-up edge that was deposited by the previous test. The carbide cutting tools used to machine the two composites were 0.3175" (9.52 mm) wide and therefore three separate cuts of width 0.1" (2.54 mm) could be performed before any edge refurbishing was required. It was hoped that by staggering the section of the tool edge in use from test to test, the effects of tool wear could be minimized.

A complete set of results can be found in Appendix I for the orthogonal experiments on the 2024-T351 alloy and the 2124 composite with 15% SiC_w. No such analysis could be conducted on for the semi-orthogonal tests. The next section reports the major trends observed during the investigation.

DISCUSSION OF RESULTS

Tests on 2024-T351 aluminum

Before analyzing the effect of various cutting parameters on the composite specimens, the results from the 2024-T351 aluminum cutting tests will be examined. This material is very similar to the 2124 aluminum used as the matrix material of the composites and thus the results from these tests can be used as benchmarks. The response of the composites can then be compared to these baseline tests the show the effect of adding silicon carbide whiskers on the cutting behavior of 2124 aluminum.

Figures 5 and 6 on the following pages show the effect of cutting speed and depth of cut on the two measured cutting forces, F_c and F_t. Figure 5 shows that both forces decrease as cutting speed is increased from 100 surface feet per minute (sfpm) to 1450 sfpm. A drop of 13 pounds (15%) is observed for the main cutting force while the thrust force is seen to decrease by 19 lbs. (37%). This result is not surprising, as the recent push toward high speed machining of aluminum alloys by industry is based on an observed decrease in forces as cutting speed is increased [4]. The force drop at high cutting speeds is characteristic of 6061-T6 [5] and 7075 aluminum alloys [6]. Since these alloys pose no serious tool wear problems, higher cutting speeds lead directly to higher production rates.

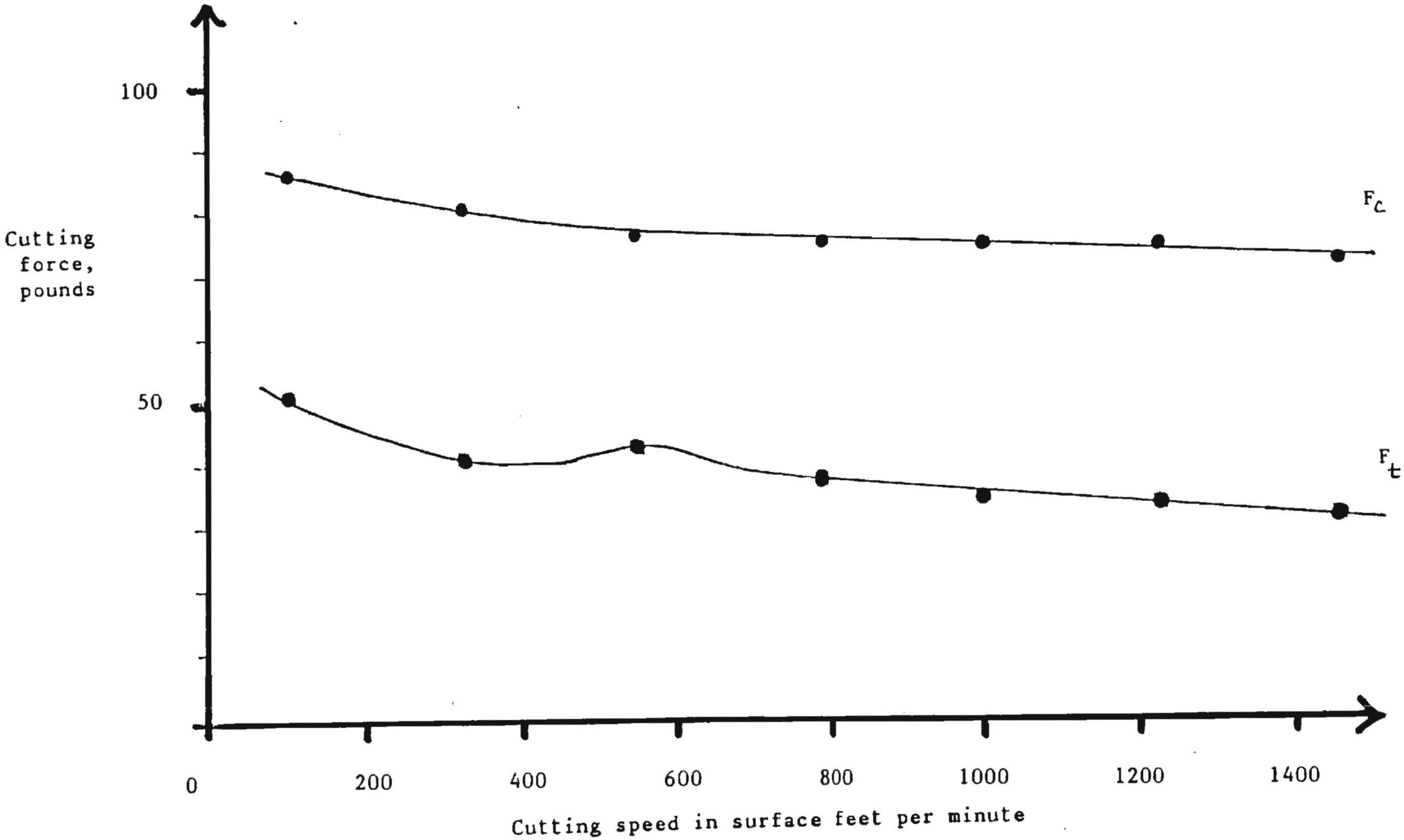


Figure 5. Cutting forces F_c and F_t versus cutting speed for 2024-T351 aluminum, $\alpha = +5°$, $t_1 = 0.0047"$.

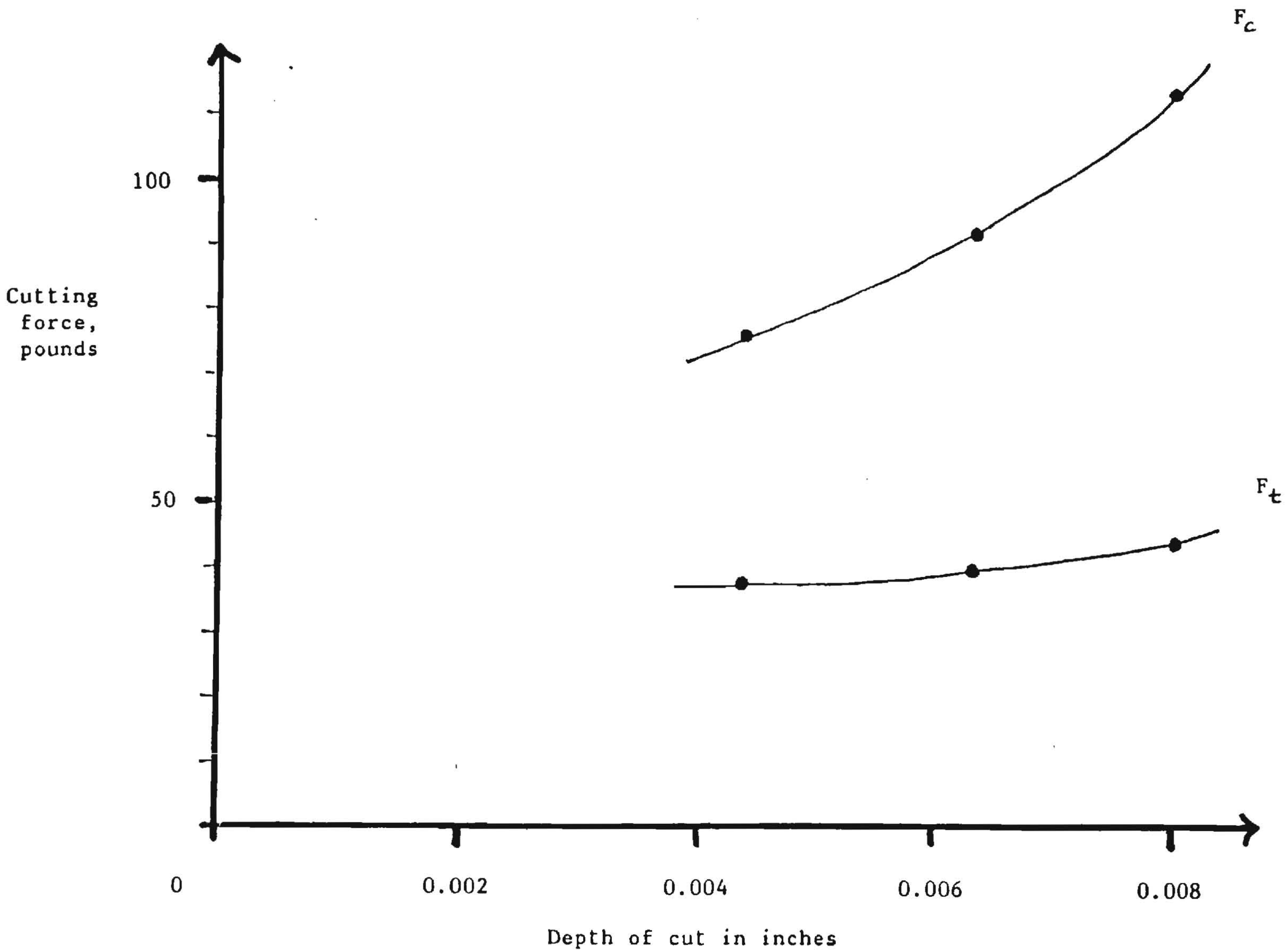


Figure 6. Cutting forces F_c and F_t versus depth of cut for 2024-T351 aluminum, α = +5°, V = 775 sfpm.

An increase in cutting forces with depth of cut is shown in Figure 6. However, the increase in cutting forces is not proportional to the increase in the depth of cut. The main cutting force increases 50% (38 lbs.) for a 70% increase in the depth of cut while the thrust force shows only a 16% (6 lb.) increase. This data suggests that large depth of cut tests are more economical in terms of energy consumed than small depth of cut tests. The specific energy of a cut (u) is a quantity defined as the power used divided by the metal removal rate. In equation form, this appears as:

$$u = \frac{(F_c)(V)}{(b_1)(t_1)(V)} = \frac{F_c}{(b_1)(t_1)} \qquad (1)$$

where b_1 is the width of cut. The trends displayed in Figures 5 and 6 show that the specific cutting energy is minimized for 2024-T351 aluminum at large depths of cut and high cutting speeds.

The third major variable examined in this study was the effect of the rake angle on the machining process. Overall, it was observed that the tests performed with a $+10^\circ$ back rake angle yielded lower forces than the tests performed with a $+5^\circ$ back rake angle. Table 2 summarizes the differences in cutting forces observed for the 2024-T351 aluminum when cut with a rake angle of $+5^\circ$ and $+10^\circ$.

The thrust force is affected the most by the change in rake angle which implies that the friction conditions along the rake face of the tool are altered by a change in tool geometry. Physically, this change in back rake angle reduces the tendency of the chip to stick to the tool. Thus the chip slides easier and the friction force, F, shows a decrease.

Table 2. Effect of rake angle on cutting forces

Measured forces	Average difference in forces $F\|_{\alpha=5^\circ} - F\|_{\alpha=10^\circ}$	Average percent difference
Cutting force, F_c	2 lbs.	2.2%
Thrust force, F_t	7 lbs.	16.4%

This same explanation applies to the decrease in forces observed as cutting speed is increased. Figure 7 plots the tool forces versus cutting speed and shows that the force parallel to the rake face of the tool, the friction force F, is most affected by an increase in cutting speed. The interface between the tool rake face and the chip has been termed the secondary shear zone, since microscopic welding or seizure occurs due to the high normal stresses on the tool. Under conditions of seizure, chip flow occurs via a shearing of the welded chip material in a direction parallel to the rake of the tool. Higher temperatures at this interface, caused by higher cutting speeds, lowers the shear stress of the chip material so that the force necessary to cause chip flow decreases. Thus, large positive rake angle tools would be preferred for machining 2024-T351 aluminum in order to minimize tool forces.

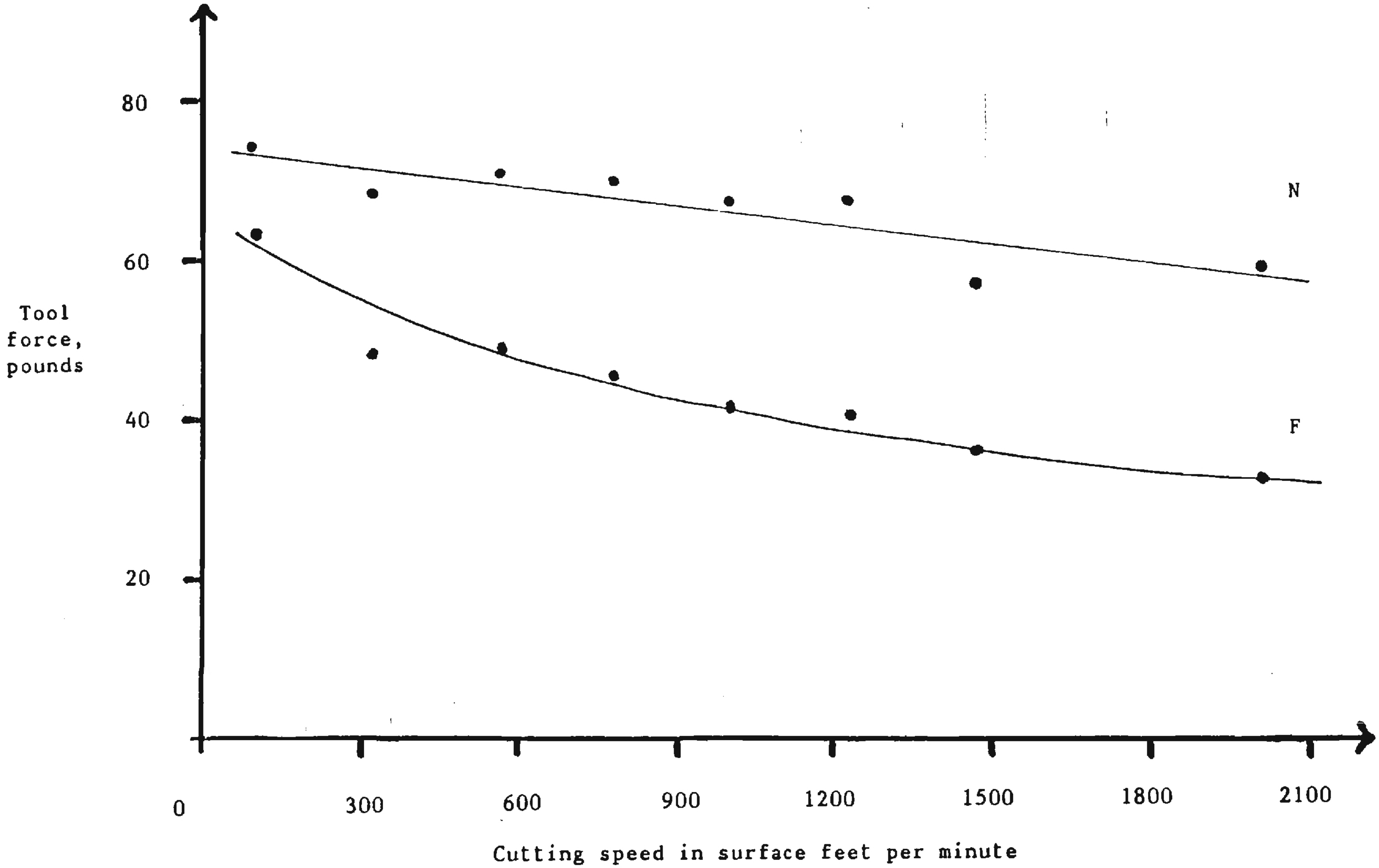


Figure 7. Tool forces F and N versus cutting speed for 2024-T351 aluminum, $\alpha = +10^{o}$, $t_1 = 0.0047''$.

Tests on 2124 aluminum containing 15% SiC_w

Data from the cutting tests on the 2024-T351 aluminum showed that minimum cutting forces could be obtained by cutting at high speeds with positive rake angle tools. Also, tests run with large depths of cut proved to be the most economical.

Data recorded from the continuous cutting tests on the MMC reinforced with 15% SiC whiskers did not show such distinct trends as for the base material. For instance, as cutting speed was increased, the measured forces did not show a definite decrease for all rake angles and depths of cut tested. The tests run with a 0° back rake and a depth of cut of 0.0063" and the tests run with a +5° back rake angle and a depth of cut of 0.0063" did show a force decreses as speed was increased. However, other series of tests at these rake angles showed maximum forces in the 550, 775 sfpm cutting speed range or contained a spurious piece of data that obscured any trend. Based on this data, the use of high cutting speeds is not recommended for this composite since the trend of decreasing forces is not clearly identifiable and since tool wear would be expected to increase at higher speeds.

Tests run with the -5° back rake angle tool showed the unexpected result of having maximum cutting forces at the lowest depth of cut. Also, these forces remained relatively constant as cutting speed was increased. The negative rake angle tool yielded the lowest cutting forces for the largest depth of cut. The measured force values, averaged over all cutting speeds tested, are presented in Table 3. These results suggest that the negative rake tool be used for roughing cuts and that the positive rake tool be used for finishing cuts.

Table 3. Average cutting force (F_c) for continuous cutting of 2124 aluminum containing 15% SiC whiskers.

Back rake angle \ Depth of cut	0.0047"	0.0063"	0.0080"
-5°	80	70	75
0°	87	97	107
+5°	74	89	84
+10°	68	N.A.	N.A.

Complete results for tests run with a rake angle of +10° are not included in Table 3 because it was not possible to run a complete series of tests as with the other tool geometries. This was due to excessive tool chatter which occurred at the larger two depths of cut. The results from the tests run with t_1 = 0.0047" are listed and support the recommendation that tools with positive rake angles be used for finishing cuts in order to minimize tool forces.

Excessive tool chatter was characterized by noticable scalloping of the workpiece surface. This instability in the process occurred to some degree at almost all of the tests run with a depth of cut of 0.0080 inches. Tests run where tool chatter was significant generally yielded a very fine, discontinuous chip that came off the workpiece in a spray. Figure 8 shows the chip type that resulted for tests conducted at various cutting speeds and depths of cut. The back rake angle of the

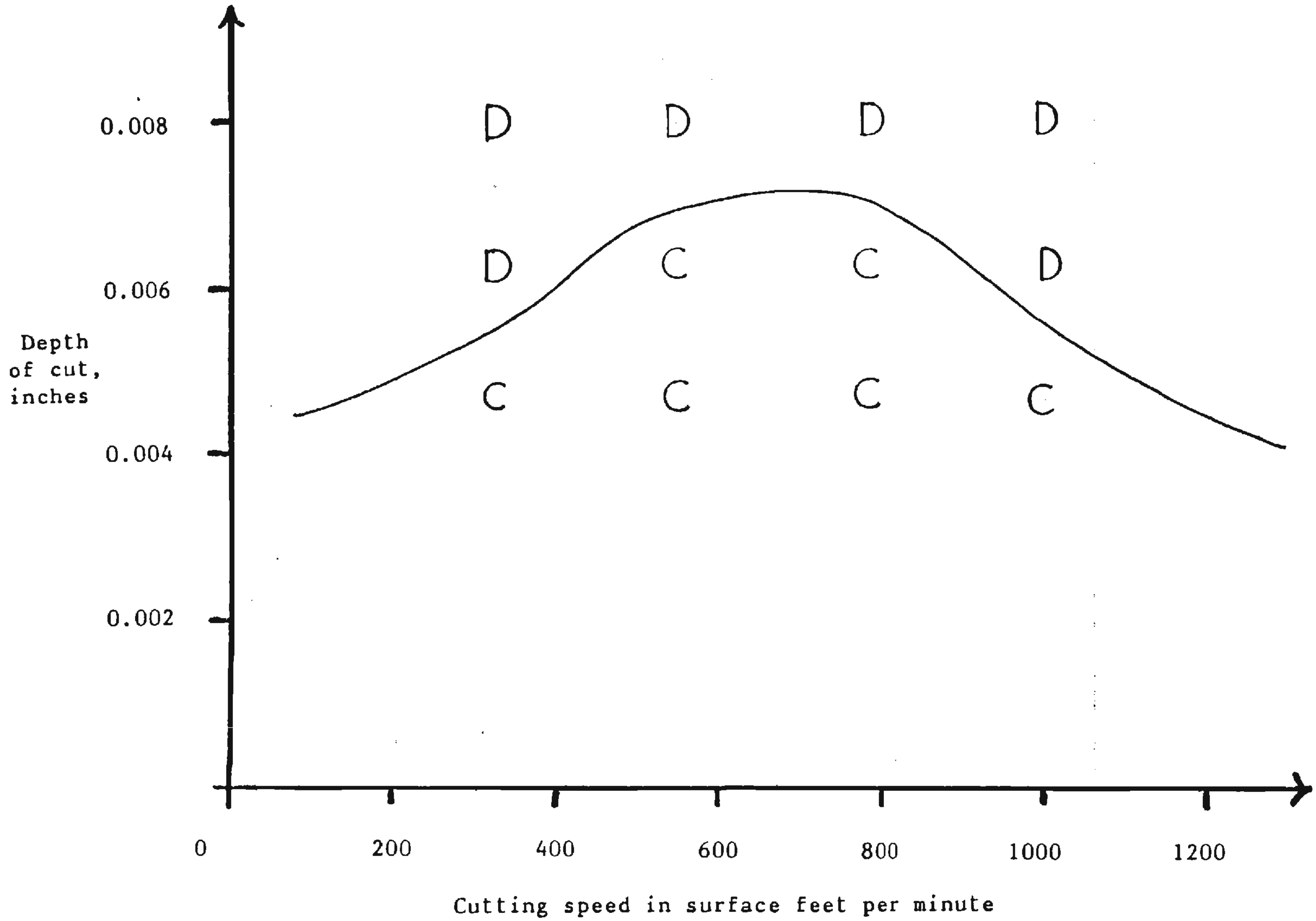


Figure 8. Plot of chip type for tests run on the 15% SiC_w composite, C = continuous chip, D = discontinuous chip.

tool did not affect this plot.

It is not clear at this point whether the discontinuous chip structure resulted from a lack of rigidity of the machine tool system which exhibibted itself primarily at large depths of cut, or whether the tool chatter was initiated by a change from uniform to localized deformation in the chip. Albrecht [7] has studied the change in chip type from continuous to what he calls cyclic and points out that cyclic chip formation is a strong source of instability in the cutting process. Thus, the scalloped work surface could be the result of cyclic tool forces that accompany the formation of the so-called cyclic chip. Photomicrographs of cut chips very closely resemble pictures of cyclic chips included in Albrecht's paper [7] and support the idea that a change in chip form does occur for this MMC at large depths of cut. The series of micrographs presented in Figures 9, 10 and 11 show a gradual change in chip form as the depth of cut is increased. In Figure 9, the serrated region is limited to the edges of the chip whereas the chip pictured in Figure 11 shows much larger serrations that extend into the center of the chip. Sectioning and etching of a cut chips is planned to clearly determine whether a cyclic chip is indeed formed.

The application of a cutting lubricant did not affect the machining of the 15% SiC_w composite. Alumicut® fluid was flooded onto the cutting tool and workpiece during tests at various cutting speeds for a depth of cut of 0.0047". There was no noticable change in the force traces or in the chip form as a result of adding the fluid. The fluid probably did not penetrate the chip/tool interface due to the high pressure in this region and thus did not function as a lubricant. A

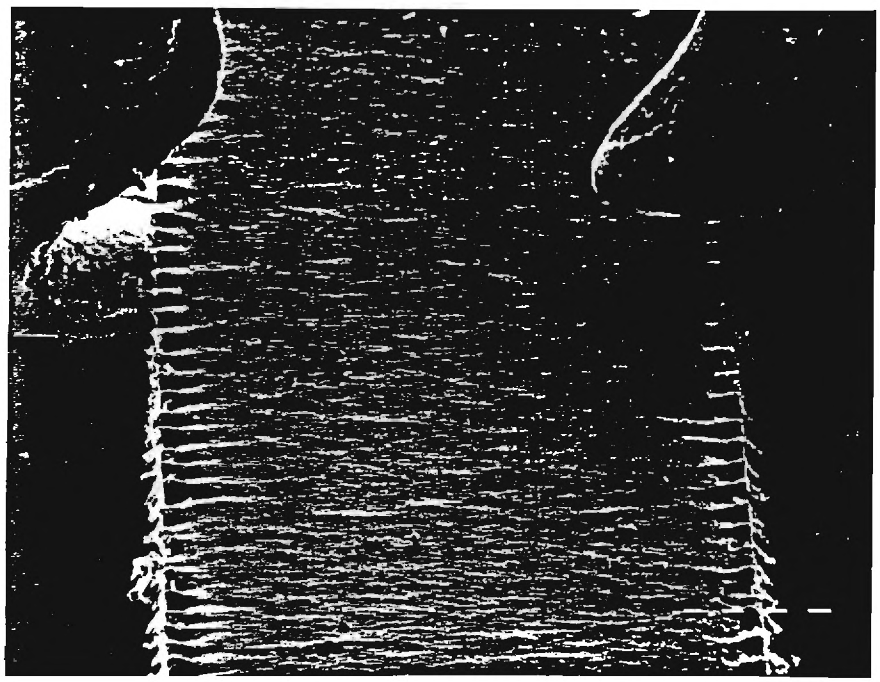


Figure 9. Micrograph of a chip of 2124-T6 aluminum with 15% SiC_w machined at a depth of cut of 0.0047", V = 1000 sfpm., $\alpha = +5^{\circ}$. Magnification = 25X.

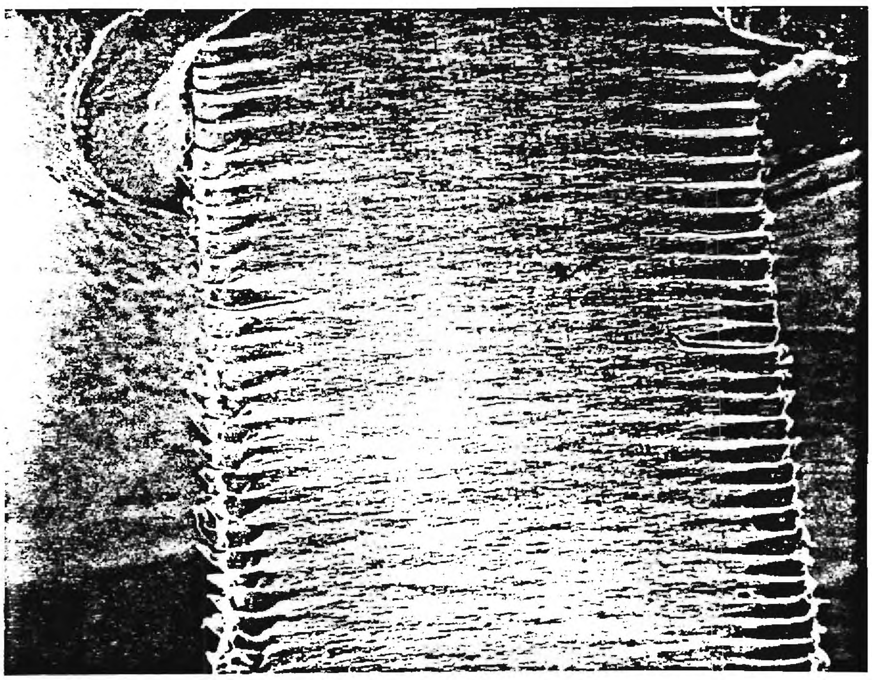


Figure 10. Micrograph of a chip of 2124-T6 aluminum with 15% SiC_{ω} machined at a depth of cut of 0.0063", V = 1000 sfpm., $\alpha = +5^{\circ}$. Magnification = 25X.

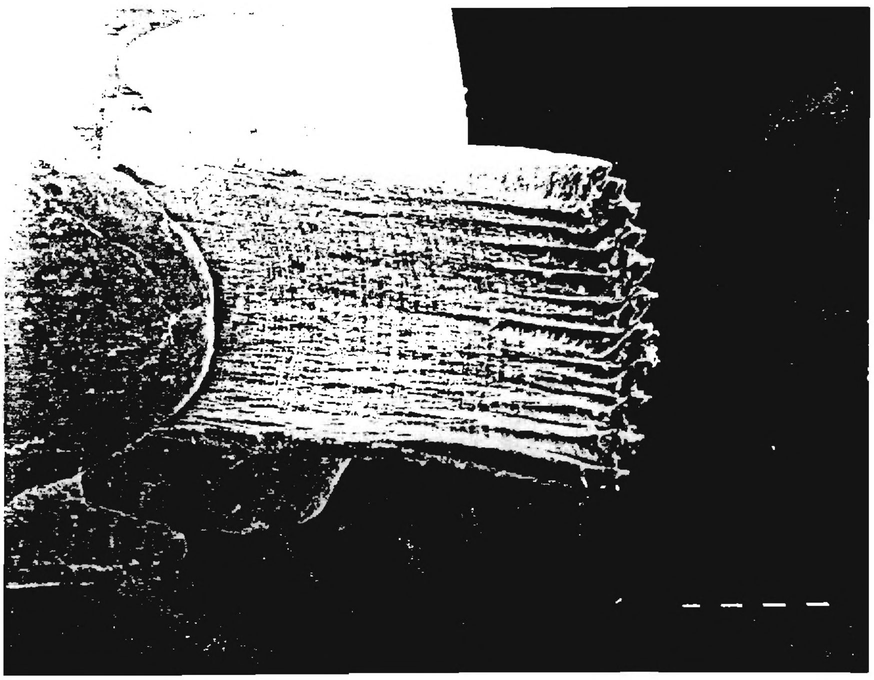


Figure 11. Micrograph of a chip of 2124-T6 aluminum with 15% SiC_w machined at a depth of cut of 0.0080", V = 1000 sfpm., $\alpha = +5^\circ$. Magnification = 25X.

cutting fluid which functions mainly as a coolant might be more useful.

To this point, the discussion of results has dealt only with tests run using the continuous cutting set-up shown in Figure 2a. The interrupted cut tests suffered from severe tool chatter over most of the cutting conditions examined in this study. The oscilloscope traces for these tests were very erratic and it was impossible to obtain an accurate force measurement in many cases. However, some of the experimental force values for the interrupted cuts correlated well with their continuous counterparts while others differed significantly. The shock load felt by the workpiece upon each revolution placed a premium on firmly gripping the workpiece in the four-jaw chuck. But it is felt that the thinness of this specimen and the warpage it recieved due to prior sawing contributed to a lack of rigidity of the system. Thus, the interrupted cut set-up was abandoned for further use on MMC specimens with a thickness of 0.25 inches. In Appendix I, the interrupted cut tests are numbered 441 through 470.

To determine the effect of adding silicon carbide whiskers on the cutting behavior of aluminum, the results from the tests on the 2024-T351 aluminum and the 2124 composite aluminum with 15% SiC_w can be compared. This comparison is limited to the tests performed using a tool with a $+5^{\circ}$ back rake angle as this was the only common tool geometry used for the tests on these two materials.

The composite specimen did not show higher forces for all cutting conditions as might have been expected. The composite specimen actually showed lower forces for most of the cuts performed at the cutting speeds of 325 and 550 sfpm. This result is due to the low shear angle (ϕ) of the 2024 aluminum cuts in this speed range that creates a larger shear area and hence, larger forces. This is precicely the reason that high cutting speeds are recommended for common aluminums. As cutting speed is increased, the 2024 aluminum begins to show lower forces that the composite, particularly at the smaller depths of cut. Table 4 presents these force trends with the resultant force, R, being the total force on the tool. The table shows that the addition of silicon carbide whiskers does not significantly alter the magnitude of the cutting forces required to machine 2024 aluminum.

Table 4. Comparison of cutting forces between 2024-T351 aluminum and 2124 aluminum with 15% SiC_w, $\alpha = +5°$.

Cutting speed	Depth of cut	2024 Al			2124 Al + 15% SiC_w		
		F_c	F_t	R	F_c	F_t	R
325	0.0047"	81	41	91	60	50	78
	0.0063"	103	58	118	76	56	94
	0.0080"	126	58	143	81	62	102
550	0.0047"	77	43	88	78	59	98
	0.0063"	97	47	108	92	44	102
	0.0080"	117	41	124	63	57	85
775	0.0047"	76	38	85	79	53	95
	0.0063"	92	40	103	98	58	114
	0.0080"	114	44	122	94	51	107
1000	0.0047"	75	35	83	77	52	93
	0.0063"	73	33	80	90	49	102
	0.0080"	85	49	98	99	51	111

Another interesting result was that the experimental shear stress of the composite sample was significantly less than the shear strees of the unreinforced sample. The 2024 aluminum had a flow stress of 47,700 psi (329 MPa) with a standard deviation of 2,000 psi. (14 MPa) which agrees with the accepted value for this material [8]. The 2124 aluminum containing 15% SiC_w had a measured flow stress of only 38,900 psi. (268 MPa) with a larger standard deviation of 9,300 psi. (64 MPa). It is possible that the brittle SiC whiskers cause the chip deformation of the composite to be more characteristic of a fracture phenomenon than a shear phenomenon. Thus, less force might be required to remove the chip. Alternatively, if the chip form of the composite does turn out to be of a cyclic nature, the analysis used to determine the shear stress is incorrect. Komanduri has discussed the pitfalls of applying a Merchant analysis to materials such as titanium that yield highly cyclic chips [9]. Further examination of the chip structures should resolve this question.

Tests on 2124 aluminum containing 20% SiC_w

The composite with 20% SiC_w was not available in the same quantity as the 15% SiC_w specimen so it was decided to perform semi-orthogonal cutting on this specimen in order to conserve material. A full series of tests was conducted on this material using a tool with a +5° back rake angle. The same semi-orthogonal tests were performed on the 15% SiC_w

composite so that the effect of differing percent volume fractions of SiC_w could be studied. Unfortunately, the force data from tests run on both composites were confounded by tool wear since semi-orthogonal cutting necessitated the use of the same portion of the cutting edge of the tool for each test. The forces generally increased with each successive cut regardless of the depth of cut or cutting speed. Likewise, the magnitudes of the recorded forces did not differ significantly. The wear of the carbide cutting tools caused this portion of the study to yield inconclusive results.

The semi-orthogonal tests did confirm some of the qualitative trends observed for the orthogonal tests. The low depth of cut tests generally yielded continuous chips and a smooth workpiece surface while the large depth of cut tests showed the tendency to form discontiuous chips and a scalloped workpiece surface. Several semi-orthogonal tests were inadvertantly conducted with a tool with a +5° back rake angle and a zero degree end relief angle. The measured forces for these tests were approximately 100 pounds greater than for the tests run with an end relief angle of 5°. However, the surface finish of the workpiece was much smoother for these tests which suggests that a smaller end relief angle might help prevent tool chatter.

CONCLUSIONS

Summarizing the discussion of results section, the following conclusions and recommendations can be made regarding the machining characteristics of the three aluminum alloys investigated in this study.

1). The 2024-T351 aluminum exhibited machining characteristics similar to common aluminum alloys such as 6061 and 7075. Tool forces decreased as cutting speed was increased and large positive rakes also yielded lower forces. Therefore, it is recommended that 2024-T351 aluminum be machined at high speeds with large positive rake angle tools and at large depths of cut in order to minimize the energy consumption of the operation.

2). The 2124 aluminum composite with 15% SiC_w did not show a decrease in cutting forces as cutting speed was increased for the range of variables tested in this study. For this reason, high cutting speeds are not recommended for this material since tool wear would be greater at high cutting speeds.

3). Based on the cutting conditions tested in this study, negative rake angle tools are recommended for large depth of cut, roughing cuts while positive rake angles are recommended for small depth of cut, finishing cuts for the 15% SiC_w composite. These rake angle/depth of cut combinations are suggested in order to minimize tool forces.

4). The use of Alumicut® cutting fluid did not affect the cutting forces for the 15% SiC_w composite.

5). The magnitudes of the cutting forces for each of the three workpiece materials did not differ greatly. The addition of silicon carbide whiskers to an aluminum matrix does not impose serious power demands on the machine tool. However, carbide tooling is inadequate for these MMCs as the whiskers do pose a serious tool wear problem.

6). The measured flow stress of the 2124-T6 aluminum reinforced with 15% SiC_w was significantly less than the flow stress of the 2024-T351 aluminum.

RECOMMENDATIONS FOR FUTURE WORK

The following recommendations for future work can be made based on the conclusions drawn from this initial portion of the study.

1). Additional repititions of the cutting tests performed on the two metal matrix composites are recommended to verify conclusively the cutting force trends reported here. The problem of tool wear as well as the variable nature of the cutting process itself requires that repititions of the tests be run in order to develop an acceptable confidence level on the stated results.

2). Analysis of the surface finish of the workpieces should be conducted to determine the cutting conditions that yield the best finish. A profilometer should be used to measure surface roughness as well as waviness induced by tool chatter.

3). The phenomenon of a cyclic chip should be investigated. Proper sectioning and etching of cut chip samples will reveal the cutting conditions that favor the formation of such a chip. Knowledge of the cutting conditions under which a cyclic chip forms is important since this chip type contributes to tool chatter and thus gives a poor surface finish.

Recommendation 1 is the most important since a high degree of accuracy concerning the observed machining characteristics of the metal matrix composites must be realized before the suggested cutting parameters are implemented in a production environment. Repeated testing is the only way to develop a high confidence level.

The anticipated investigation of cyclic chip formation, a phenomenon which affects tool chatter and therefore surface finish, is of more of an academic interest. A cyclic chip is not usually observed when cutting the 2000 series wrought aluminum alloys. The formation of such a chip must be attributed to the addition of the silicon carbide whiskers. This result points to the development of a material deformation model to predict the conditions necessary for a particular workpiece to yield a cyclic chip in a metal cutting operation. Once developed, such a model could be used to define and avoid the cutting conditions that favor cyclic chip formation for a wide range of workpiece materials.

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Appendix I

Orthogonal cutting data for 2024-T351 aluminum and 2124-T6 aluminum with 15% SiC whiskers

Test numbers	Material
400 - 440	2124-T6 aluminum with 15% SiC_w, continuous cutting
441 - 470	2124-T6 aluminum with 15% SiC_w, interrupted cutting
550 - 580	2024-T351 aluminum, continuous cutting

Nomeclature

TEST = Experimental test number
RAKE = Back rake angle on cutting tool in degrees
SPEED = Cutting speed in surface feet per minute (sfpm)
D.O.C. = Depth of cut in inches
FC = Main cutting force in pounds
FT = Thrust force in pounds
PHI = Shear angle in degrees
FS = Shear force in pounds
FN = Normal force on shear plane in pounds
F = Friction force in pounds
N = Normal force on tool rake face in pounds
TAU = Shear stress in psi.
GAMMA = Shear strain
SIGMAN = Normal stress on shear plane in psi.
MU = Coefficient of friction along tool rake face
HP = Horsepower required to perform cut

TEST	RAKE	SPEED	D.O.C.	FC	FT	PHI	FS	FN	F	N	TAU	GAMMA	SIGMAN	MU	HP
400	0	325	.0047	84.5	55.8	29.5	46.0	90.2	55.8	84.5	48262.	2.33	94558.	.66	.8
401.	0	325	.0063	102.5	66.5	34.1	47.6	112.5	66.5	102.5	42344.	2.15	100190.	.65	1.0
402	0	325	.0080	120.5	82.7	36.8	47.0	138.4	82.7	120.5	35170.	2.09	103585.	.69	1.2
403	0	550	.0047	95.3	84.5	****	****	*****	84.5	95.3	******	****	*******	.89	1.6
404	0	550	.0063	96.2	81.8	****	****	*****	81.8	96.2	******	****	*******	.85	1.6
405	0	550	.0080	101.6	86.3	****	****	*****	86.3	101.6	******	****	*******	.85	1.7
406	0	775	.0047	84.5	68.3	36.7	26.9	105.3	68.3	84.5	34208.	2.09	133933.	.81	2.0
407	0	775	.0063	95.3	66.5	37.5	35.1	110.8	66.5	95.3	33902.	2.07	107144.	.70	2.2
408	0	775	.0080	98.9	83.6	****	****	*****	83.6	98.9	******	****	*******	.85	2.3
409	0	1000	.0047	82.7	67.4	37.6	24.4	103.9	67.4	82.7	31651.	2.07	134879.	.81	2.5
410	0	1000	.0063	93.5	73.7	****	****	*****	73.7	93.5	******	****	*******	.79	2.8
411	0	1000	.0080	106.1	96.2	****	****	*****	96.2	106.1	******	****	*******	.91	3.2
412	-5	325	.0047	82.7	62.0	31.3	38.5	95.9	54.6	87.8	42524.	2.38	105938.	.62	.8
413	-5	325	.0063	64.7	80.0	****	****	*****	74.1	71.4	******	****	*******	1.04	.6
414	-5	325	.0080	.0	86.3	****	****	*****	86.0	7.5	******	****	*******	****	.0
415	-5	550	.0047	70.1	89.9	****	****	*****	83.4	77.7	******	****	*******	1.07	1.2
416	-5	550	.0063	70.1	80.9	****	****	*****	74.5	76.9	******	****	*******	.97	1.2
417	-5	550	.0080	80.0	96.2	****	****	*****	88.9	88.	******	****	*******	1.01	1.3
418	-5	775	.0047	80.9	69.2	32.3	31.4	101.7	61.9	86.6	35716.	2.34	115605.	.71	1.9
419	-5	775	.0063	73.7	106.1	****	****	*****	99.3	82.7	******	****	*******	1.20	1.7
420	-5	775	.0080	71.9	93.5	****	****	*****	86.9	79.8	******	****	*******	1.09	1.7
421	-5	1000	.0047	85.4	66.0	36.6	29.3	103.9	58.3	90.8	37086.	2.23	131724.	.64	2.6
422	-5	1000	.0063	71.0	109.7	****	****	*****	103.1	80.3	******	****	*******	1.28	2.2

TEST	RAKE	SPEED	D.O.C.	FC	FT	PHI	FS	FN	F	N	TAU	GAMMA	SIGMAN	MU	HP
423	-5	1000	.0080	73.7	115.1	****	****	*****	108.2	83.5	******	****	*******	1.30	2.2
424	5	325	.0047	60.2	50.4	34.6	21.0	75.7	55.5	55.6	25304.	2.02	91388.	1.00	.6
425	5	325	.0063	76.4	55.8	37.6	26.5	90.8	62.2	71.2	25654.	1.94	87951.	.87	.8
426	5	325	.0080	80.9	62.0	****	****	*****	68.8	75.2	******	****	*******	.92	.8
427	5	550	.0047	78.2	59.3	36.7	27.3	94.3	65.9	72.7	34711.	1.96	119749.	.91	1.3
428	5	550	.0063	91.7	44.1	39.0	43.5	92.0	51.9	87.5	43466.	1.91	91875.	.59	1.5
429	5	550	.0080	62.9	56.6	****	****	*****	61.9	57.7	******	****	*******	1.07	1.0
430	5	775	.0047	79.1	53.1	37.1	31.1	90.1	59.8	74.2	39859.	1.95	115599.	.81	1.9
431	5	775	.0063	98.0	58.4	39.4	38.7	107.3	66.7	92.5	38990.	1.90	108024.	.72	2.3
432	5	775	.0080	93.5	51.3	****	****	*****	59.3	88.7	******	****	*******	.67	2.2
433	5	1000	.0047	77.3	52.2	40.5	24.9	89.9	58.7	72.5	34440.	1.88	124083.	.81	2.3
434	5	1000	.0063	89.9	48.6	43.3	32.0	97.0	56.3	85.3	34893.	1.85	105721.	.66	2.7
435	5	1000	.0080	98.9	51.3	****	****	*****	59.7	94.1	******	****	*******	.64	3.0
436	10	325	.0047	61.1	59.3	****	****	*****	69.0	49.9	******	****	*******	1.38	.6
437	10	325	.0063	66.5	67.4	34.9	16.0	93.3	77.9	53.8	14552.	1.90	84667.	1.45	.7
438	10	550	.0047	71.0	47.7	35.1	30.6	79.9	59.3	61.6	37505.	1.89	97716.	.96	1.2
439	10	775	.0047	66.5	36.9	38.2	29.5	70.1	47.9	59.1	38743.	1.81	92239.	.81	1.6
440	10	1000	.0047	73.7	47.1	44.7	19.3	85.3	59.2	64.4	28887.	1.70	127577.	.92	2.2
441	0	325	.0047	78.7	34.8	47.5	27.4	81.6	34.8	78.7	43088.	2.01	128026.	.44	.8
442	0	325	.0063	99.8	44.3	33.0	59.6	91.5	44.3	99.8	51500.	2.19	79119.	.44	1.0
443	0	325	.0080	118.0	54.0	****	****	*****	54.0	118.0	******	****	*******	.46	1.2
444	0	550	.0047	78.7	37.1	36.3	41.5	76.5	37.1	78.7	52230.	2.10	96325.	.47	1.3

TEST	RAKE	SPEED	D.O.C.	FC	FT	PHI	FS	FN	F	N	TAU	GAMMA	SIGMAN	MU	HP
445	0	550	.0063	98.5	42.7	41.6	45.3	97.3	42.7	98.5	47762.	2.01	102522.	.43	1.6
446	0	550	.0080	112.4	45.0	****	****	*****	45.0	112.4	******	****	*******	.40	1.9
447	0	775	.0047	81.6	38.0	35.5	44.4	78.3	38.0	81.6	54830.	2.12	96621.	.47	1.9
448	0	775	.0063	96.9	40.7	35.3	55.6	89.2	40.7	96.9	50967.	2.12	81808.	.42	2.3
449	0	775	.0080	108.6	35.5	****	****	*****	35.5	108.6	******	****	*******	.33	2.6
450	0	1000	.0047	76.0	33.7	38.1	39.0	73.4	33.7	76.0	51233.	2.06	96299.	.44	2.3
451	0	1000	.0063	97.3	40.5	****	****	*****	40.5	97.3	******	****	*******	.42	2.9
452	0	1000	.0080	106.8	59.1	****	****	*****	59.1	106.8	******	****	*******	.55	3.2
453	5	325	.0047	95.8	52.8	****	****	*****	60.9	90.8	******	****	*******	.67	.9
454	5	325	.0063	103.9	50.6	****	****	*****	59.5	99.1	******	****	*******	.60	1.0
456	5	550	.0047	79.1	39.6	****	****	*****	46.3	75.3	******	****	*******	.62	1.3
457	5	550	.0063	95.5	50.6	****	****	*****	58.7	90.7	******	****	*******	.65	1.6
459	5	775	.0047	70.1	40.7	****	****	*****	46.7	66.3	******	****	*******	.70	1.6
460	5	775	.0063	92.6	45.0	****	****	*****	52.9	88.3	******	****	*******	.60	2.2
463	5	1000	.0063	92.6	45.0	****	****	*****	52.9	88.3	******	****	*******	.60	2.8
465	10	325	.0047	78.7	43.2	****	****	*****	56.2	70.0	******	****	*******	.80	.8
470	10	550	.0080	89.9	61.8	****	****	*****	76.5	77.8	******	****	*******	.98	1.5

TEST	RAKE	SPEED	D.O.C.	FC	FT	PHI	FS	FN	F	N	TAU	GAMMA	SIGMAN	MU	HP
550	5	100	.0047	86.3	52.2	18.3	65.6	76.6	59.5	81.4	43732.	3.27	51075.	.73	.3
551	5	325	.0047	80.9	41.4	21.5	60.1	68.2	48.3	77.0	46856.	2.84	53136.	.63	.8
552	5	325	.0063	102.5	57.6	23.0	71.8	93.1	66.3	97.1	44599.	2.68	57875.	.68	1.0
553	5	325	.0080	125.9	66.5	24.2	87.5	112.3	77.2	119.6	44901.	2.57	57636.	.65	1.2
554	5	550	.0047	77.3	43.2	22.9	54.4	69.9	49.8	73.2	45027.	2.69	57814.	.68	1.3
555	5	550	.0063	97.1	46.8	25.3	67.7	83.9	55.1	92.7	46013.	2.48	56977.	.59	1.6
556	5	550	.0080	116.9	41.1	27.1	85.4	89.8	51.1	112.9	48564.	2.36	51047.	.45	1.9
557	5	775	.0047	75.5	37.8	26.5	50.7	67.5	44.2	71.9	48134.	2.40	64101.	.62	1.8
558	5	775	.0063	91.7	39.6	27.3	63.3	77.3	47.4	87.9	46110.	2.35	56282.	.54	2.2
559	5	775	.0080	113.8	44.1	28.8	78.5	93.5	53.9	109.5	47254.	2.26	56259.	.49	2.7
560	5	1000	.0047	75.2	34.9	25.1	53.3	63.5	41.3	71.9	48109.	2.50	57348.	.57	2.3
561	5	1000	.0063	89.9	38.6	27.5	61.9	75.8	46.3	86.2	45388.	2.33	55547.	.54	2.7
562	5	1000	.0080	108.3	38.6	29.3	75.6	86.7	47.9	104.5	46218.	2.23	53009.	.46	3.3
563	5	1225	.0047	75.2	34.9	25.8	52.5	64.1	41.3	71.9	48621.	2.45	59371.	.57	2.8
564	5	1450	.0047	73.4	33.1	28.9	48.3	64.4	39.4	70.2	49616.	2.26	66198.	.56	3.2
565	10	100	.0047	84.6	48.7	20.8	61.8	75.6	62.7	74.9	46689.	2.82	57101.	.84	.3
566	10	325	.0047	76.2	36.0	23.4	55.6	63.3	48.7	68.8	47035.	2.55	53561.	.71	.8
567	10	325	.0063	101.6	48.7	25.7	70.5	87.9	65.6	91.6	48463.	2.36	60459.	.72	1.0
568	10	325	.0080	124.8	55.0	25.4	89.2	103.2	75.8	113.4	47777.	2.38	55268.	.67	1.2
569	10	550	.0047	78.3	36.0	24.9	55.9	65.6	49.0	70.9	50021.	2.42	58701.	.69	1.3
570	10	550	.0063	92.5	39.4	26.9	64.6	77.0	54.9	84.3	46467.	2.27	55408.	.65	1.5
571	10	550	.0080	113.1	41.1	27.7	81.0	89.0	60.1	104.2	47080.	2.22	51674.	.58	1.9
572	10	775	.0047	77.1	32.5	25.5	55.5	62.6	45.4	70.3	50966.	2.37	57412.	.65	1.8
573	10	775	.0063	92.5	36.0	28.8	63.8	76.1	51.5	84.8	48699.	2.16	58082.	.61	2.2

TEST	RAKE	SPEED	D.O.C.	FC	FT	PHI	FS	FN	F	N	TAU	GAMMA	SIGMAN	MU	HP
574	10	775	.0080	106.0	32.2	30.1	75.6	81.0	50.1	98.8	47347.	2.09	50704.	.51	2.5
575	10	1000	.0047	73.8	30.3	27.5	51.4	61.0	42.7	67.4	50580.	2.24	59941.	.63	2.2
576	10	1000	.0063	90.9	32.2	30.6	61.9	73.9	47.5	83.9	49960.	2.07	59687.	.57	2.8
577	10	1000	.0080	106.0	28.4	29.7	78.0	77.2	46.4	99.5	48311.	2.11	47811.	.47	3.2
578	10	1225	.0047	73.8	28.4	27.0	52.9	58.8	40.8	67.7	51063.	2.27	56808.	.60	2.7
579	10	1450	.0047	66.5	25.2	29.5	45.5	54.7	36.4	61.1	47635.	2.12	57266.	.60	2.9
580	10	2000	.0047	68.3	21.6	30.4	48.0	53.2	33.1	63.5	51667.	2.08	57315.	.52	4.1