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Comparative Evaluation of Rescue Saw Blades for Forcible Entry Into Advanced Composite Material Aircraft

July 2015

Final Report

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16. Abstract

New aircraft designs use significant quantities of advanced composite materials, which presents a new challenge to aircraft rescue and firefighting personnel: how to safely cut into composite materials when responding to incidents involving these aircraft. This report provides guidance regarding forcible entry on aircraft that are composed of mostly advanced composite materials using a circular saw.

A cutting test apparatus and procedure were developed to measure the force exerted by a saw blade on a panel made with aircraft-grade, advanced composite materials, as well as measuring blade wear and particulate production caused by this type of cutting. Tests were conducted to compare the performances of three different types of saw blades: metal, concrete, and diamond-tipped. Each saw blade was tested by cutting panels of various thicknesses of aluminum, GLAss-REinforced aluminum laminate (GLARE), and carbon fiber-reinforced plastic (CFRP). These tests examined saw blade cutting performance in both dry and wet cutting conditions.

When comparing the force measurements from all the panels and saw blades, the diamond-tipped saw blades cut through both the GLARE and CFRP panels easier than the aluminum panels. Under wet cutting conditions, the metal and concrete saw blades had the highest forces for all three materials. Mass and diameter loss were more apparent during the dry cuts than the wet cuts. Of the three saw blades, the concrete saw blades had the most mass and diameter loss. Particulate analysis showed that the diamond-tipped saw blades released the smallest amount of particulates of all three saw blades.

Overall, the diamond-tipped saw blade exerted the least amount of force, had the least wear, and released the least amount of particulates, thereby concluding it to be the best choice of the three saw blade types for use on composites.

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LIST OF ACRONYMS AND ABBREVIATIONS

AL04	Aluminum, thickness 0.04 inch
AL06	Aluminum, thickness 0.06 inch
AL08	Aluminum, thickness 0.08 inch
ARFF	Aircraft Rescue and Firefighting
ATRD	Airport Technology Research and Development
CFRP	Carbon fiber-reinforced plastic
CF16	16-ply carbon fiber
CF24	24-ply carbon fiber
DAQ	Data acquisition
FAA	Federal Aviation Administration
F_A	Axial force
F_P	Plunge force
GLARE	GLAss-REinforced aluminum laminate
G3	GLARE, thickness 0.10 inch
G5	GLARE, thickness 0.14 inch
HEPA	High-efficiency particulate absorption
IFSTA	International Fire Service Training Association
NIOSH	National Institute for Occupational Safety and Health
RPM	Revolutions per minute
TO	Technical Order
USAF	United States Air Force

EXECUTIVE SUMMARY

To improve cost and weight factors, the current trend in new aircraft designs is to use significant quantities of advanced composite materials. These composites have helped reduce fuel consumption thus lowering operational costs. This trend presents new challenges for Aircraft Rescue and Firefighting (ARFF) personnel when responding to incidents involving theses aircraft. Among other safety considerations, ARFF personnel must know how to safely cut composite materials to forcibly enter the aircraft during a fire or incident. This report provides guidance regarding forcible entry using a circular saw on aircraft that are composed of mostly advanced composite materials.

Research team technicians conducted practical trials to evaluate the cutting performance of various saw blade types on different aluminum thicknesses, but these trials did not provide enough data and were not statistically reliable. Due to these results, a cutting test apparatus and a test procedure were developed to measure forces exerted by a saw blade on a panel made of aircraft-grade advanced composite material. Evaluations also examined measuring saw blade wear and particulate production from each cutting trial. Tests were conducted using this apparatus to compare the performances of three different types of saw blades: metal, concrete, and diamond-tipped. The saw blades were tested by cutting panels of various thicknesses of aluminum, GLAss-REinforced aluminum laminate (GLARE), and carbon fiber-reinforced plastic (CFRP). These tests examined saw blade cutting performance in both dry and wet conditions.

When comparing the force measurements from all panels and saw blades, it was determined that the diamond-tipped saw blades cut through both the GLARE and CFRP panels more easily than the aluminum panels. The metal and concrete saw blades had the highest forces of all three materials when it came to wet cuts. Of the three saw blades, the metal ones were the most difficult to use, and they broke when trying to cut thick CFRP during wet cuts. Mass and diameter loss were more apparent during the dry cuts than the wet cuts. Of the three saw blades, the concrete saw blades had the most mass and diameter loss. Particulate analysis showed that, of the three saw blade types, the diamond-tipped blade released the smallest amount of nanoparticulates.

Overall, the diamond-tipped saw blades exerted the least amount of force, showed the least amount of wear, and released the least amount of particulates, thereby determining it to be the best choice of the three saw blade types for use on composites.

1. INTRODUCTION.

In many aircraft incidents, Aircraft Rescue and Firefighting (ARFF) personnel duties often include performing forcible entry into an aircraft with unserviceable doors or entrance hatches. For this type of aircraft entry, the Federal Aviation Administration (FAA), National Fire Protection Association, and International Civil Aviation Organization recommend the use of a portable, gasoline-driven, metal cutting saw. Although these saws can include chain saws and reciprocating saws, circular saws are the most commonly used type. These saws are often equipped with multipurpose or multimaterial cutting saw blades. These saw blades allow ARFF personnel to cut through the various aircraft materials without having to change saw blades or switch saws.

New aircraft designs use significant quantities of advanced composite materials. Therefore, ARFF personnel must know how to safely cut through composite materials when responding to incidents involving these aircraft. To provide the ARFF community with this knowledge, the FAA Airport Technology Research and Development (ATRD) Branch, located at the William J. Hughes Technical Center in Atlantic City, New Jersey, commissioned research into using circular saws for cutting through aircraft composite materials.

1.1 PURPOSE.

This report provides guidance to the ARFF community regarding the relative performance of different saw types on various materials used in modern aircraft. Specifically, this report documents the results of cutting trials that compared the cutting forces on aircraft aluminum, carbon fiber, and fiber metal laminate advanced aircraft composites.

1.2 BACKGROUND.

Traditionally, aircraft fuselages were constructed of aluminum alloys, both for structural frame members and fuselage skin. Although some unstressed aircraft parts were made of fiberglass (e.g., cowling panels and empennage fairings), the bulk of the aircraft structure was aluminum. The drive for stronger, stiffer, and lighter materials has brought about the creation and widespread adoption of advanced aircraft composites.

1.2.1 Composite Materials.

Advanced aircraft composites include GLAss-REinforced aluminum laminate (GLARE), carbon fiber-reinforced plastic (CFRP), and honeycomb sandwich panels constructed of aluminum or composite outer panels bonded to an aluminum, phenolic, or aramid honeycomb core. Advanced composites have weight savings and other advantages over aluminum; thus, these materials are increasingly used in aircraft construction. Honeycomb panels are typically used on flight control surfaces and in the aircraft interior, and they are not as likely to require cutting during ARFF operations; therefore, only GLARE and CFRP were considered for this research effort.

1.2.1.1 GLAss-REinforced Aluminum Laminate.

GLARE is a composite constructed by alternating plies or layers of aluminum with layers of glass fibers and epoxy resin. The combination of fiberglass and aluminum gives the material better fatigue and impact damage tolerance than aluminum alone. As cracks form in the aluminum layers, the stress across the crack is bridged by the adjoining fiberglass layers, confining the crack to a local area; this prevents the crack from propagating through the thickness of the material. If necessary, the glass fibers can be oriented in a desired direction to tailor material properties, similar to what is done with CFRP. Currently, GLARE panels are found in the fuselage upper section of the Airbus A380. Figure 1 shows material composition of the A380 aircraft and sections that are made of GLARE and CRFP [1].

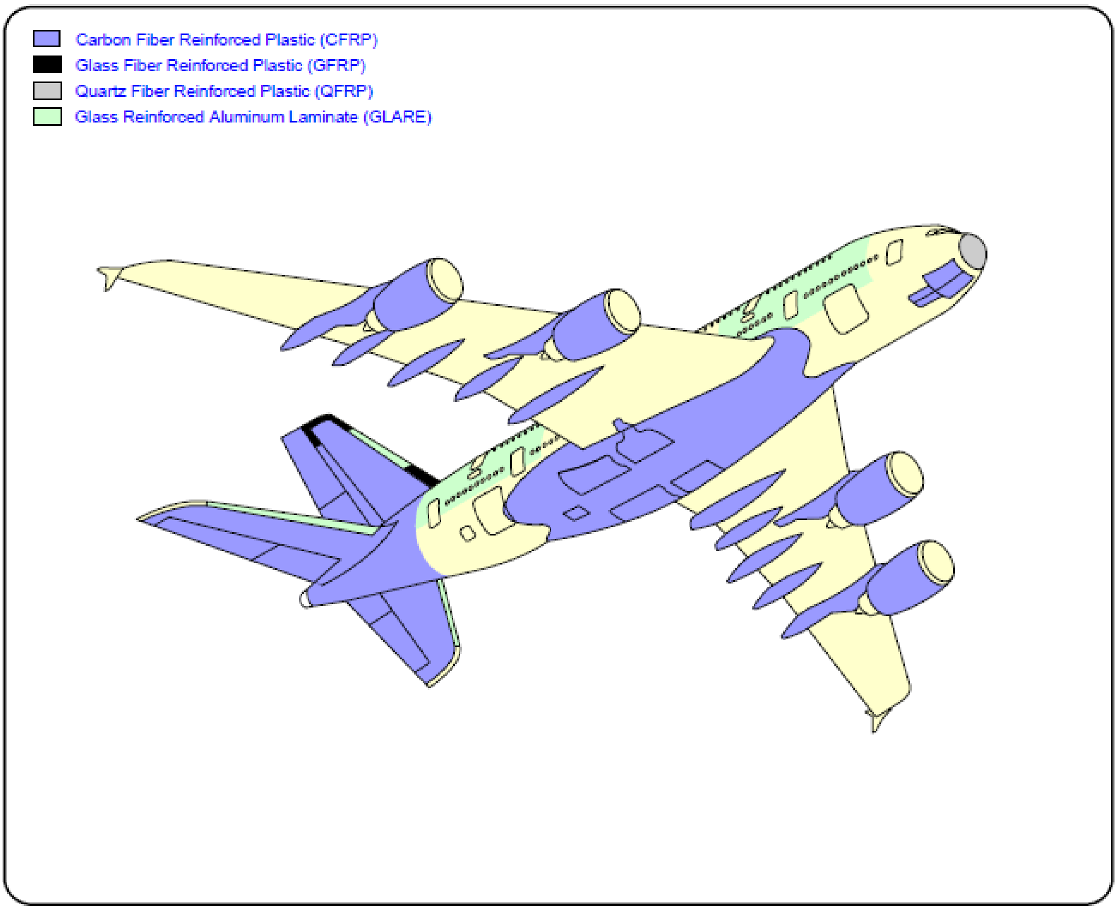

Figure 1. Composite Makeup of Airbus A380 [1]

1.2.1.2 Carbon Fiber-Reinforced Plastic.

CFRP is constructed by reinforcing bulk plastic with carbon fibers. While nominally serving as a means of reinforcement for the plastic, the fibers in fact provide a majority of the material's strength. The plastic primarily serves to hold the fibers in place and to protect them from environmental stresses, such as debris and changing air temperatures. It also helps distribute and transfer stresses to the fibers, protects against abrasion and water infiltration, and provides additional toughness to the material. The plastics used can vary by application; however, toughened epoxy resins are used in most aerospace applications.

Carbon fibers are lightweight, strong, and stiff (in the direction of the fiber), and can hold considerable tensile stress and a moderate degree of compressive stress. However, the fibers do not have much practical value on their own due to their flexible nature, which results in a limp form when they are not supported by another material. Embedding fibers inside a plastic matrix provides form and controls the bulk shape and placement of the fibers. This also allows for controlling the strength of the material by tailoring it to the expected stresses in each application (i.e., more fibers where higher stresses are expected). Therefore, material is added only where it is actually needed. This further reduces weight compared to traditional materials. High natural strength-to-weight ratio, high fatigue strength, and corrosion resistance are additional benefits, particularly for aerospace applications.

Currently, two aircraft use CFRP for a majority of the aircraft's composition. The first is the Boeing B787. Figure 2 shows that this aircraft is made of 50% composite with CFRP being the leading composite [2]. The second aircraft is the Airbus A350-900. Figure 3 shows that the A350-900, like the B787, is mostly comprised of CFRP composites [3].

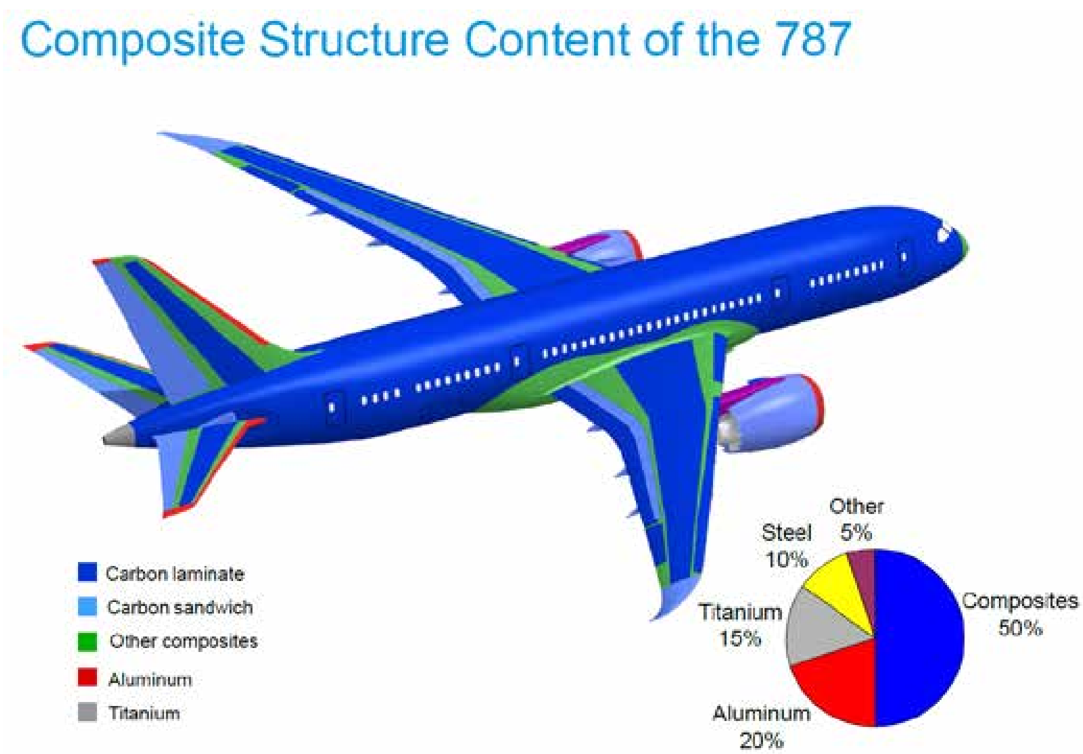

Figure 2. Composition of the Boeing B787 [2]

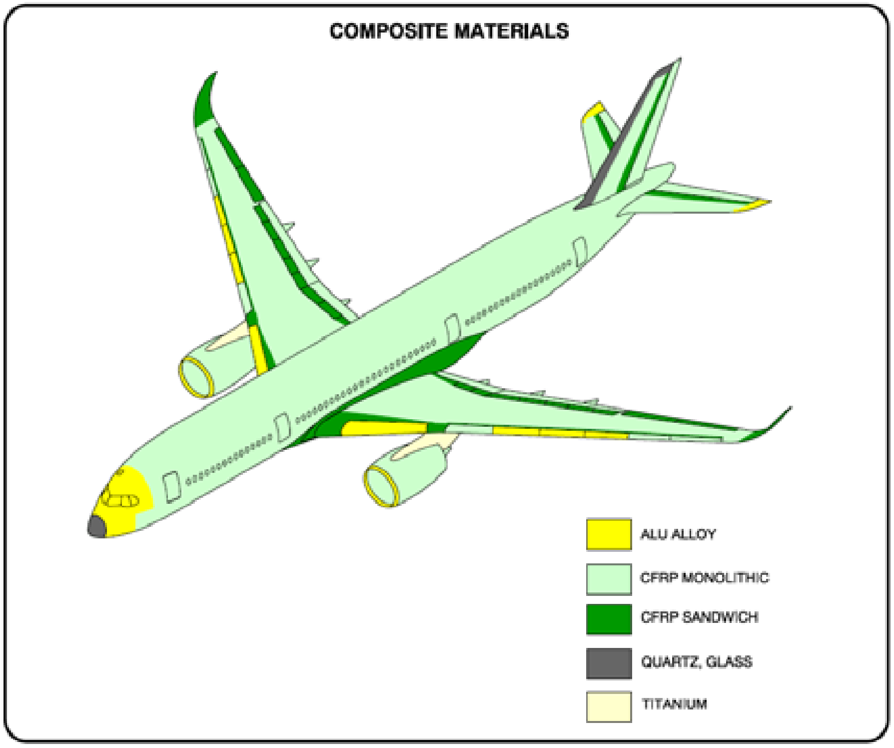

Figure 3. Composite Materials of the Airbus A350-900 [3]

1.2.2 Fuselage Cutting.

Aircraft emergencies can sometimes result in rendering the aircraft doors inoperable or inaccessible. To deal with these instances, ARFF personnel are trained to use forcible entry techniques to gain access to the interior of the aircraft. This traditionally involves using cutting tools to create openings into the fuselage. Circular saws are the most common type of forcible entry tools used by ARFF personnel according to the International Fire Service Training Association (IFSTA) [4]. Forcible entry training most often entails cutting into aluminum aircraft. Due to the availability and expense of composite materials, ARFF personnel rarely have experience cutting into advanced composites during forcible entry training. Therefore, research was initiated to give ARFF personnel insight into aircraft composites and what to expect when performing composite cutting operations.

1.2.2.1 Rescue Saw Types.

There are currently four types of rescue saws available to ARFF personnel [4]. The most common type is the gas-powered circular saw. This saw runs on an internal combustion engine that uses a fuel/oil mixture, resulting in a high amount of vibration and loud noise. The second type is the electric saw, which can be powered by either an electric cord or a battery. These saws are much quieter than gas-powered saws and produce less vibration [4]. With electric-powered saws, ARFF personnel would not only need an extension cord, which could create a tripping hazard, but would also need a power source nearby. With battery-powered saws, ARFF personnel need to ensure that the battery is fully charged and have spare batteries in case the first battery runs out of power. The hydraulic saw is the third type. This saw uses a pump to produce and transmit pressure through a liquid to make the tool operational [4]. The liquid is transferred from the pump to the saw via a hose (whose length depends on the type of pump that is used, i.e., a standalone system or a backpack module). Most hydraulic pumps tend to be gasoline operated. If the saw being used is part of a standalone system, ARFF personnel must ensure they have a sufficient amount of hose to reach the fuselage, which could create a tripping hazard to other ARFF personnel. A backpack module allows the operator to move to various locations without the concern of hose length, but this adds to the amount of weight a responder needs to carry when responding to an incident. The final type of rescue saws used is the pneumatic saw [4]. This saw operates similar to hydraulic saws but uses compressed air instead of a liquid.

1.2.2.2 Saw Blade Types.

According to IFSTA, all rotary saw blades should be rated heavy-duty and have the capability of using a 16-inch diameter saw blade [4]. A 16-inch saw blade is recommended to cut through a combination of fuselage skin, frame members, and interior panels, thus allowing for faster forcible entry. It is recommended that during cutting operations, the saw blade and surface being cut must simultaneously be cooled with a water spray. This cooling prevents the aluminum being cut from melting and fouling the cutting surface and from creating sparks that could ignite fuel that could be present.

Circular saw blades are generally either single-point-cut (toothed) or abrasive. Toothed saw blades remove material from a surface by carving out and chipping away material. Abrasive saw blades work by similar principles, but the carving and breaking down of the material occurs on a much smaller scale. With many cutting points working at the same time, abrasive removal of material seems continuous and smooth compared to a toothed saw blade. Both material removal methods generate heat as well as chips or dust, although the chips and dust vary in size according to the saw blade used. The heat generated from the cut comes from both friction and the mechanical cutting actions of deforming and breaking away material. This often results in the chips and dust becoming hot enough to glow.

The typical manufactured abrasives used in abrasive cutting are diamond, silicon carbide, and aluminum oxide. Diamond is among the hardest materials in the earth and is the hardest practical material available. Silicon carbide is hard but easily fractured by impact. Aluminum oxide is slightly softer than silicon carbide but more durable. Silicon carbide is traditionally used on hard materials with a low tensile strength (e.g., ceramics and pottery), while aluminum oxide is generally used on high tensile strength materials, such as steel [5].

In general, an abrasive wheel is called hard or soft depending on the bond strength of the binding material and not on the abrasive grains. A soft wheel is used to cut hard materials, and a hard abrasive wheel is used to cut soft materials [6].

1.2.3 Past United States Air Force Research and Guidance.

Since many United States Air Force (USAF) aircraft have a high composite composition, the USAF has been active in providing guidance and conducting research regarding composite materials. According to guidance given to ARFF personnel under Technical Order (TO) 105E-9, it is recommended that an abrasive cutoff wheel be used to cut composite materials [7]. The order recommends that "Kevlar fibers be cut by carbide tipped saw blades as recommended by its manufacturer" [7]. This TO also warns that damaged composites could absorb fuel and other combustible liquids. To reduce the chance of ignition, it is recommended that "cutting operations should be water cooled when possible" [7]. Foam should blanket the working area if there is a potentially high risk of sparking residual fuel [7].

In 2011, the Air Force Research Laboratory conducted research evaluating the performance of commonly used cutting tools on CFRP panels following a composite aircraft crashes including a B-2 Bomber [8]. ARFF personnel, when responding to this crash, reported having a difficult time cutting through the aircraft's composite surfaces. One tool used during these evaluations was a circular saw. For these tests, F-16 horizontal stabilizers and a B-2 door were used for the composite test pieces, and two, 12-inch saw blades (one metal carbide and one diamond-tipped) were used to evaluate the performances of the circular saw [8]. To maintain consistency in cutting behavior, only one operator was employed to run the saws in these evaluations. The operator was instructed to use the same amount of force throughout all the cuts and report how difficult each was to cut. The saw operator used the same saw blade to cut multiple lines on the CFRP panels until the saw blade wore out or the operator ran out of CFRP panels. Water was used to keep the saw blades cool and minimize particulate dispersion. Researchers found the operator cut at a lower speed when dealing with thicker composites and that the diamond-tipped saw blade was able to cut longer lengths than the metal carbide saw blade. The diamond-tipped saw blade also cut at a faster rate when it came to thicker composites. The saw operator also commented that the diamond-tipped saw blade had cleaner cuts [8].

1.2.4 Past Boeing Research and Guidance.

ARFF personnel conducted several cutting trials at Boeing with different tools on a B787 fuselage mockup and published their findings in a presentation made available to the ARFF community, "787 Aircraft Rescue and Firefighting Composite Structure" [2]. Their findings stated that when using a circular saw, approximately the same amount of force was required to cut into a composite as was required to cut through aircraft-grade aluminum [2].

1.3 OBJECTIVES.

The objectives of this research effort consisted of the following:

- Develop a test method to evaluate cutting forces on various materials.
- Measure and evaluate the cutting forces exerted on aluminum and composite panels both in dry and wet conditions when using different types of saw blades.
- Evaluate and compare the amount of wear on saw blades used to cut aluminum panels and on saw blades used to cut composite panels.
- Measure and evaluate the amount of particulates that are dispersed during all cutting trials.

2. PRACTICAL TRIALS.

In the beginning of this research effort, practical trials were conducted to obtain the average cutting times for two different aluminum thicknesses when using different types of circular saw blades. Since aircraft are traditionally constructed from aluminum, cuts on aluminum provided a reference for comparison. Tests were also performed to determine the amount of saw blade wear that could be expected during rescue operations and the level of effort needed to cut composites.

2.1 TEST SETUP.

The timed trials consisted of three saw operators performing quick-as-possible rough cuts on aluminum sheets. The time needed to cut 48 inches of aluminum was recorded and used to gauge cutting performance. The setup for these trials, shown in figure 4, consisted of securing a long aluminum sheet and suspending it to ease cutting. Each saw operator ran 5 cuts per saw blade. These cuts were performed with the intent of getting through the material quickly without regard for cutting saw blade wear or how hard the saw worked to make the cut. This was done to gauge a minimum-time cutting operation.

Two different aluminum thicknesses, AL04 and AL08 (0.04 and 0.08 inch), were used to represent the different thicknesses that could be found on aircrafts. A standard gas-powered circular saw (Super Vac Super-VC3) was equipped with three of the same type saw blades used by ARFF personnel: metal composite (Norton® HSM1601), concrete (Norton® HSC1601), and diamond-tipped (Husqvarna® EH5-16). A welding ventilation system was used to capture particulates dispersed by the material cutting.

Figure 4. Cutting Setup for Practical Trials

2.2 CUTTING TIMES.

Figure 5 and table 1 show the average cutting times from each saw operator when using different saw blades on different aluminum thicknesses. Figure 5 shows that although the metal and concrete saw blades had similar cutting times, operators had difficulty cutting the aluminum panels with the diamond-tipped saw blades. While cutting through the thicker aluminum panels, overall average cutting times for both metal and concrete saw blades went up by a minimum of 1.5 seconds when compared with the average times of the thinner aluminum. However, overall average cut time for the diamond-tipped saw blades rose significantly by 12 seconds compared with the thinner material. Statistical analysis was conducted on the cutting trials to see how much variation there was between each cut and if the average cutting times from each saw operator were statistically the same. Table 1 shows the average times of each operators' runs and overall averages with their corresponding standard deviation. In some cases, there was large deviation between the runs, meaning the results were not repeatable. A statistical analysis known as a "t-test," with a 95% confidence interval, was used to compare the saw operators' averages and see if they were statistically similar or different. The test showed that there were cutting scenarios in which the time averages between saw operators were statistically different. This meant that this testing method was not viable.

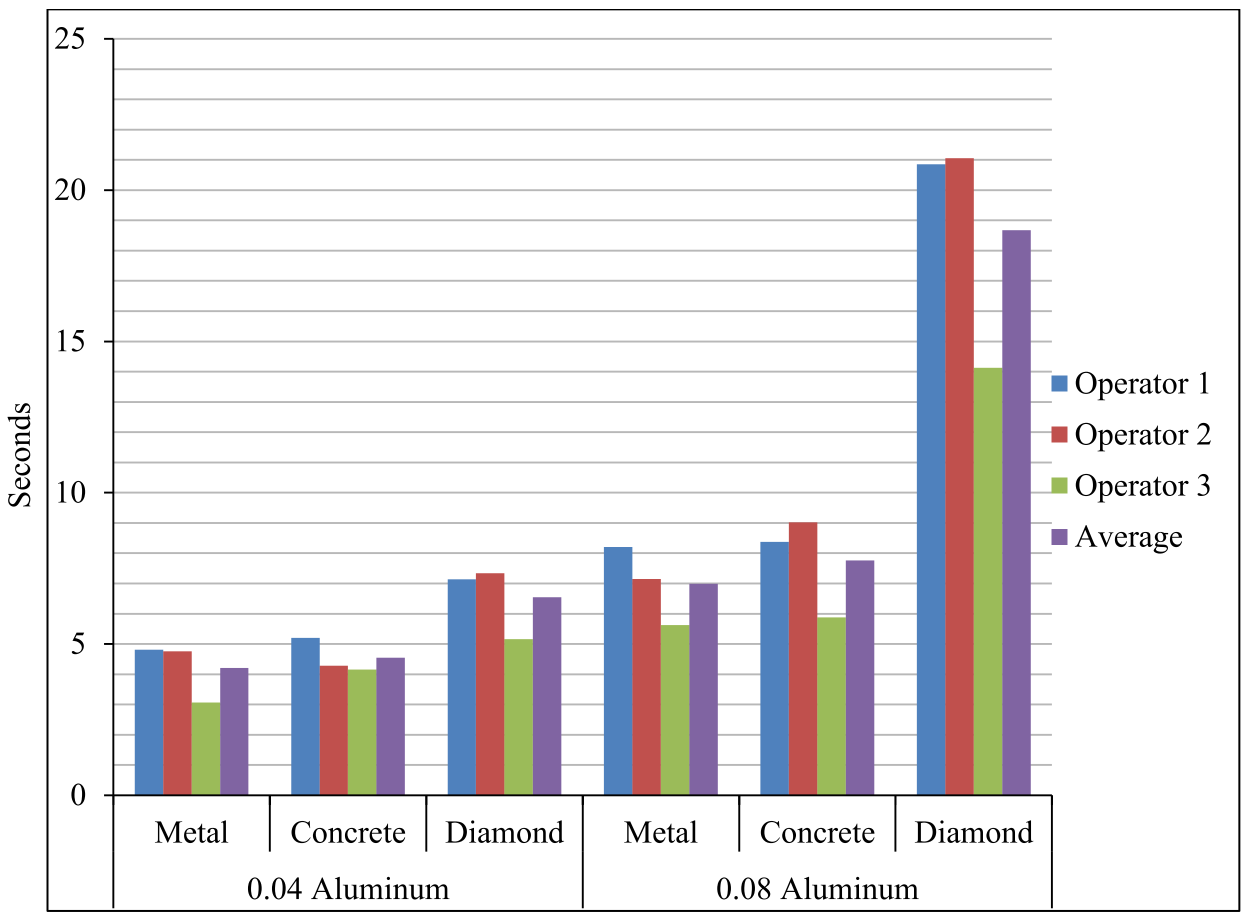

Figure 5. Average Time Comparisons for Practical Trials

Table 1. Average Cutting Times and Statistical Analysis

			Average Cutting Time (Seconds)	Standard Deviation
AL04	Metal	Operator 1	4.808	2.187
		Operator 2	4.754	0.522
		Operator 3	3.062	0.586
		Average	4.208	1.499
	Concrete	Operator 1	5.198	0.462
		Operator 2	4.284	0.704
		Operator 3	4.152	1.970
		Average	4.545	1.242
	Diamond	Operator 1	7.142	1.007
		Operator 2	7.336	0.841
		Operator 3	5.164	0.887
		Average	6.547	1.322
AL08	Metal	Operator 1	8.206	1.495
		Operator 2	7.150	0.253
		Operator 3	5.622	0.363
		Average	6.993	1.378
	Concrete	Operator 1	8.372	1.016
		Operator 2	9.024	1.018
		Operator 3	5.878	1.049
		Average	7.758	1.695
	Diamond	Operator 1	20.854	1.750
		Operator 2	21.052	2.355
		Operator 3	14.126	0.817
		Average	18.677	3.709

2.3 SAW BLADE WEAR.

The posttest saw blade conditions are shown by overlaying a used saw blade on a new saw blade, as shown in figure 6 for the concrete saw blade and figure 7 for the metal saw blade. These figures show there was significant wear on the saw blades after five cuts. This wear was caused by the saw operators cutting the aluminum sheet as quickly as possible, resulting in high cutting force. Figure 8 shows the buildup of aluminum on the diamond-tipped saw blade. This built-up aluminum made it more difficult to cut, translating to the high cutting times when the saw operators used the diamond-tipped saw blade.

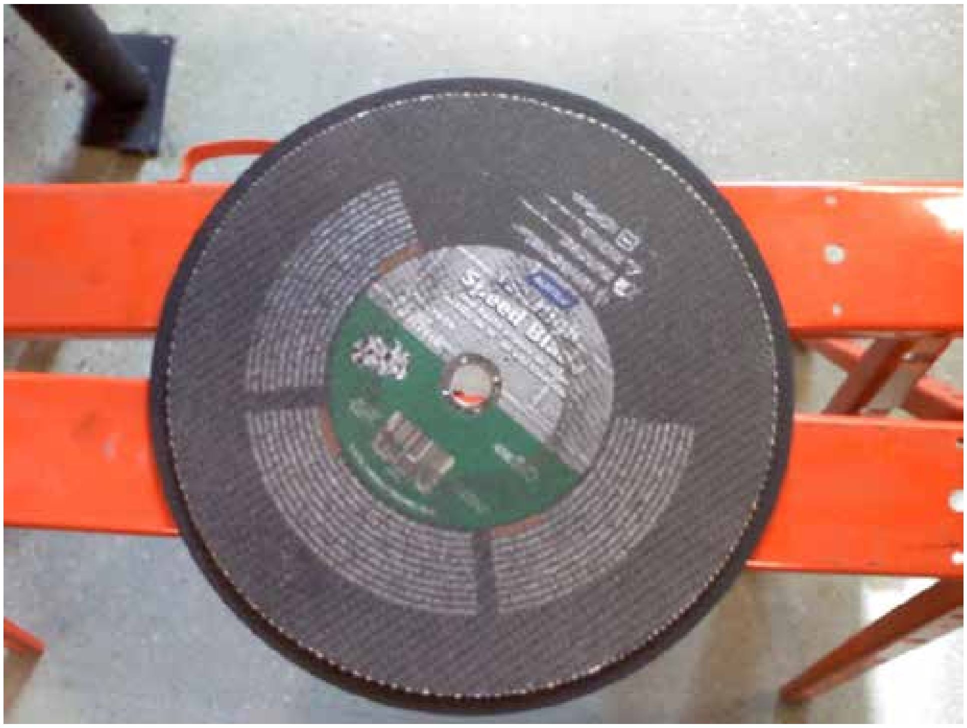

Figure 6. Concrete Saw Blade Wear Following Practical Trials

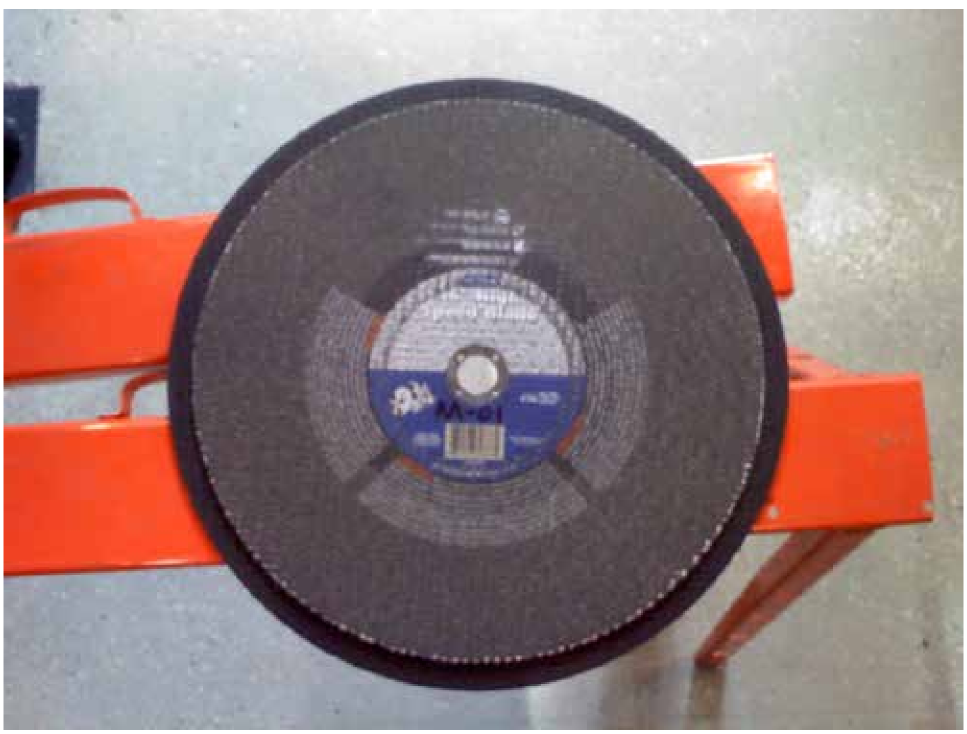

Figure 7. Metal Saw Blade Wear Following Practical Trials

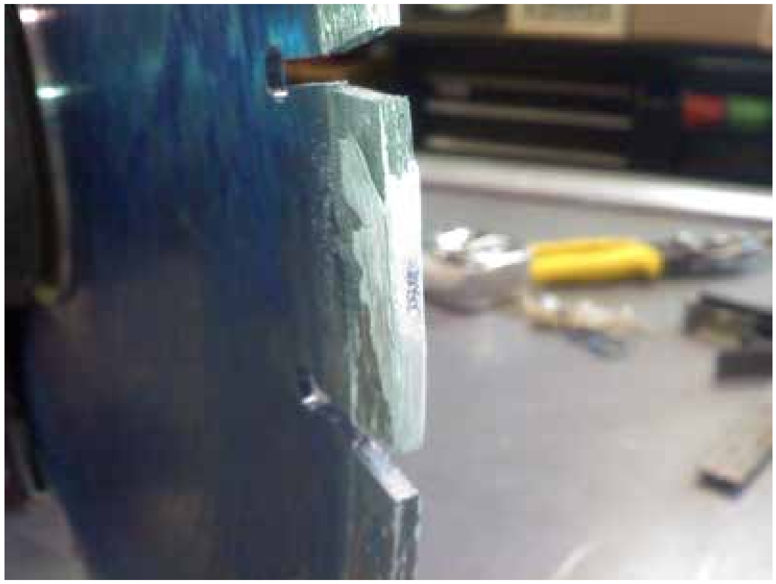

Figure 8. Aluminum Buildup on the Diamond-Tipped Saw Blade Following Practical Trials

Because the data for certain scenarios had large deviations and some averages were statistically different, the results from the practical trials could not be used for cutting evaluations with confidence. Another issue encountered was the lack of a reliable method to measure cutting forces. The saw operator could state if a panel was difficult to cut, but there was no way of confirming whether this was due to the panel's hardness or the saw operator's fatigue. Due to unreliable data and the inability to measure accurate forces, a new method was created to conduct composite cutting evaluations that reduced statistical error and could record cutting forces.

3. CUT RIG.

To obtain more reliable data, a cutting tool was created that would remove the potential error caused by the human element and would offer the ability of measuring different cutting forces. The cutting tool, known as the cut rig, consisted of a circular saw mounted on top of a robust aluminum frame, as shown in figure 9. A water line was placed adjacent to the rescue saw to simulate the operation where ARFF personnel spray the surface to prevent spark production. A mounting plate on guide rails was installed below the rescue saw where test panels would be clamped down for testing. To ensure containment control of particulates produced by the panel cutting, the cut rig was enclosed inside a small sea container with a Lexan™ view window. Container ventilation was controlled via a high-efficiency particulate absorption (HEPA) filtration system (OmniAire 2000V). The machine was positioned outside the rear of the container; and a small opening was created in the front of the container with a HEPA filter, which allowed for air circulation inside the container. A small sump pump was placed in the rear-bottom side of the container to collect waste water created during wet cuts. Because there was also an interest in the number of particulates produced from cutting, the FAA Safety Office personnel was tasked with placing particulate sample collectors inside the cut rig enclosure. These samples were then analyzed, and a summary was provided by the FAA Safety Office personnel.

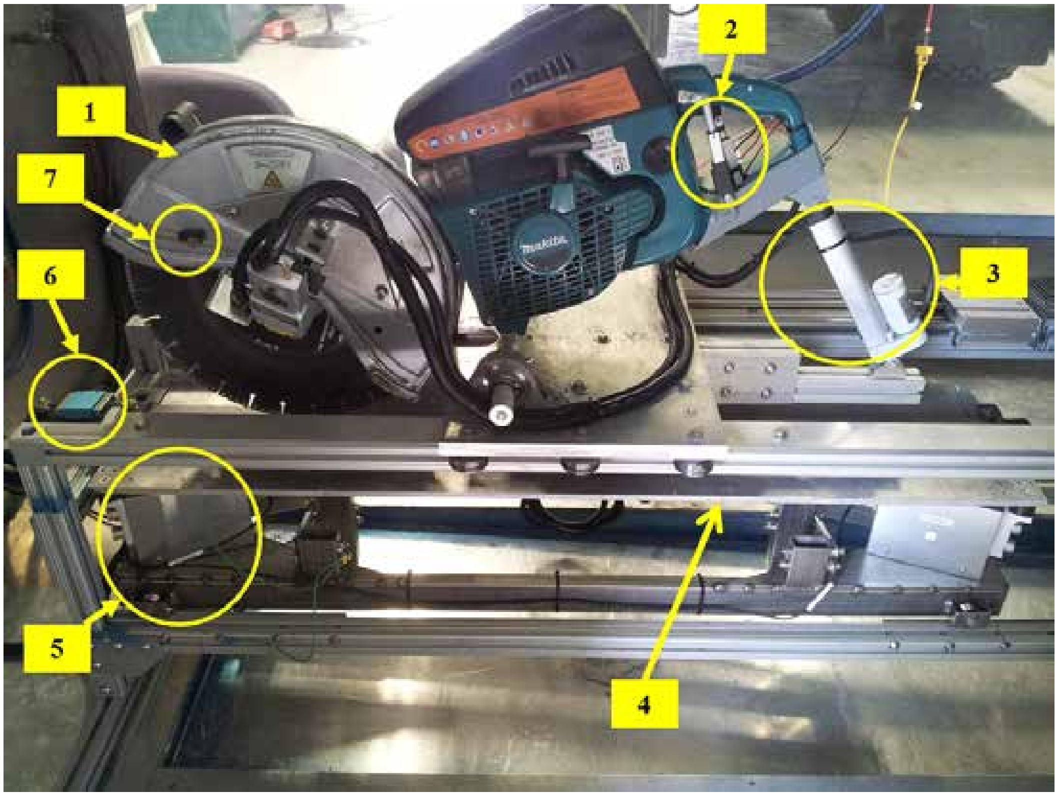

Figure 9. Cut Rig Components: (1) Rescue Saw, (2) Throttle Actuator, (3) Plunge Actuator, (4) Panel Mounting Plate, (5) Plunge Load Cell, (6) Axial Load Cell, and (7) Water Line

3.1 RESCUE SAW.

A Makita® DPC8132 Power Cutter was used as the cutting tool for all evaluations. This gasoline-powered saw is the most commonly used of all saw types. The Makita saw uses a 16-inch saw blade and has a maximum speed of 3800 revolutions per minute (RPM). Before every test series, the fuel tank level was inspected to ensure sufficient fuel was available to run all the tests.

3.2 MOTION CONTROL.

The saw was mounted on a counter lever to allow the saw to rotate and plunge down. This counter lever was mounted on a guide rail to allow horizontal and backward movement of the saw after it had cut into the panel. The plunging movement of the saw was controlled by a linear actuator mounted on the saw's handle, as shown in figure 9. A linear actuator, also shown in figure 9, was used to control the saw's throttle. The saw's horizontal forward and backward movements were controlled by a screw drive that was mounted adjacent to the cutting saw. The speed given to the screw drive was based on the overall average time from the practical cutting trials. All motion was controlled via a National Instruments™ CompactRio motion-control system.

3.3 FORCE MEASUREMENT.

For this research effort, feedback was required for two types of forces: plunge force (F_P) and axial force (F_A) was obtained. F_P is the force exerted by the saw operator when trying to cut into the panel and F_A is the force needed to pull the saw along the panel. Figure 10 shows the theoretical direction of each of the desired forces.

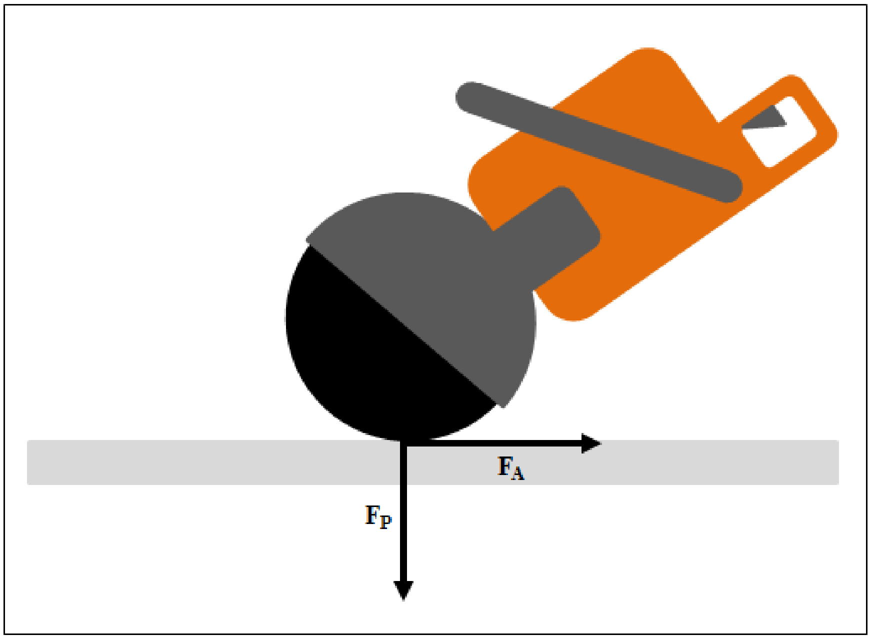

Figure 10. Forces Exerted by Saw on Cutting Material

To measure F_A, an S-beam load cell (Omega® LCCD-25, shown in figure 9) was mounted on the front of the cutting plate when the saw was cutting along the panel. To obtain vertical F_P, four platform load cells (Omega® LCAD-50, shown in figure 9) were mounted in the bottom of the cutting plate. Vibration dampeners were mounted between the cut plate and the load cells to reduce the amount of vibration forces the load cells read. These load cells were selected because of their resistance to vibration and water submersion. These were necessary qualities, since the circular saw produced high vibrations, and the load cells could be splashed with water during wet cutting trials. Force measurements were read and collected via a data acquisition (DAQ) system (National Instruments CompactDAQ). Both the motion control system and the DAQ were controlled via National Instruments LabVIEW software.

3.4 SAW BLADE TYPES.

As in the practical trials, three different saw blade types were used to conduct the tests. The Norton metal and concrete abrasive saw blades used in the practical trials were also used in these tests to represent abrasive saw blades. However, a different diamond-tipped saw blade (Cutter's Edge® CEDVBL16) was used for these tests. A new saw blade was used for each test scenario to ensure consistency with the initial saw blade length and mass and increase the accuracy of saw blade wear analysis.

3.5 TEST PANELS.

For each test scenario, two test panels of each material were used to evaluate the saw blade cutting performances. Each test panel was 12 inches wide and 48 inches long. The total cut length for each cutting trial was approximately 45 inches. Test panel materials consisted of aircraft-grade aluminum, CFRP, and GLARE. The weave and resin make of the CFRP and GLARE composites used for the cutting trials were similar to those used in aircraft manufacturing. Two different thicknesses were evaluated from each test panel material. Table 2 shows the thicknesses and number of plies of the test panel materials.

Table 2. Test Panel Material Specifications

Test Sample Code	Material	Thickness (in.)	Number of Plies
AL06	Aluminum 2024-T3	0.06	1
AL08	Aluminum 2024-T3	0.08	1
CF16	CFRP	0.10	16
CF24	CFRP	0.17	24
G3	GLARE	0.10	5 (aluminum layers) and 4 (polymer layers)
G5	GLARE	0.14	4 (aluminum layers) and 3 (polymer layers)

4. RESULTS AND DISCUSSION.

Table 3 shows the number of cuts that were run for each test scenario. A total of 24 cuts were run for a majority of the tests; however, some wet cut and metal saw blade test scenarios had to be ended prematurely (indicated by yellow highlight in table 3) due to the saw blade breaking or the cut rig binding up because forces were too high. Three categories were analyzed from these test results: cutting forces, saw blade wear, and particulate dispersion.

Table 3. Number of Cutting Attempts per Test Scenario

Panel Material	Cutting Condition	Saw Blade Type	Number of Runs
AL06	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	24
		Diamond	24
		Concrete	24
AL08	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	3
		Diamond	24
		Concrete	24
CF16	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	24
		Diamond	24
		Concrete	24
CF24	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	1
		Diamond	24
		Concrete	24
G3	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	13
		Diamond	24
		Concrete	24
G5	Dry	Metal	24
		Diamond	24
		Concrete	24
	Wet	Metal	9
		Diamond	24
		Concrete	24

4.1 CUTTING FORCES.

Cutting forces were determined by averaging the forces acquired from the load cells for all cutting attempts for each test scenario. After the measurements from each cutting attempt were averaged, the resulting values went through an ensemble average, and a low-pass filter was used to reduce noise produced during the measurement. Figure 11 shows an example of the force offset of both cutting phases. Phase 1 is the time the saw blade was plunged downward and cut into the material, and phase 2 is the time the saw blade was pulled back and cut along the material. The figure also shows force measurements when the saw did not contact the material at all. This offset was due to the weight of the material on the load cells, vibrations caused by the saw, and water that accumulated on the top of the panel during wet cuts. Since this research effort focused on the forces exerted by the saw only, the offset values for each test scenario were calculated and reduced from the each force measurement to portray true F_A and F_P values. Final graphs showing the force comparison between saw blade types on different test scenarios are provided in appendix A, and force information is shown in table 4. Force analysis examined the peak forces that occurred during phase 1 and at the overall force range during phase 2. Analysis of the average force comparisons for each material will be discussed in sections 4.1.1, 4.1.2, and 4.1.3.

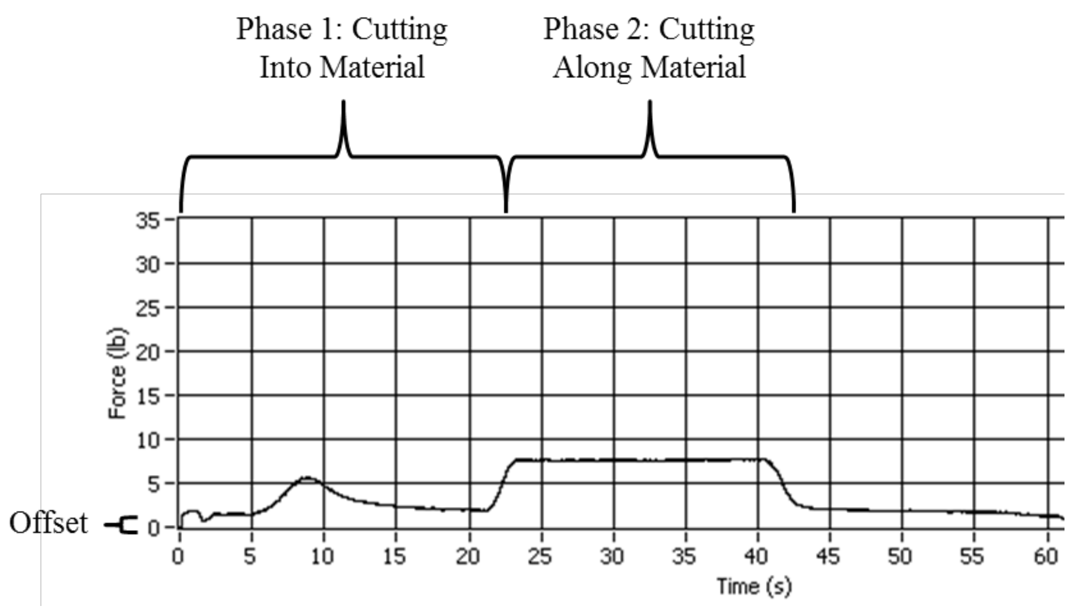

Figure 11. Example of Cutting Phases and Force Offset

Table 4. Average Force Summary for all Test Scenarios

			Cutting Phase 1		Cutting Phase 2	
Panel Material	Dry/Wet Cuts	Saw Blade Type	Average Peak F_P (lb)	Average Peak F_A (lb)	Average F_P (lb)	Average F_A (lb)
AL06	Dry	Metal	9.6	5.9	1 to 2	8
		Diamond	8.3	5.3	2	7
		Concrete	8.1	4.9	0 to 1	7
	Wet	Metal	16.9	7	2 to 3	8.5 to 9.5
		Diamond	7.8	4.5	1.5	4
		Concrete	9.5	5.9	0.5to 1	6 to 7
AL08	Dry	Metal	10.5	6.4	1 to 2	9
		Diamond	10.9	6	4.5 to 5	10 to 13
		Concrete	10	6.3	1 to 2	9
	Wet	Metal	16.9	5.3	2.5 to 3.5	8 to 7
		Diamond	9	5.2	5.5	5.5
		Concrete	12.2	8.1	1 to 1.5	8 to 9
G3	Dry	Metal	10.8	3.8	0 to 1	6.5 to 7
		Diamond	5.8	4.3	0 to 0.5	3.5
		Concrete	6.5	4.5	0	5
	Wet	Metal	19.3	4.9	2	8 to 9
		Diamond	6.7	4.1	1	3.5
		Concrete	11.3	5.2	0.5 to 1.5	5 to 5.75
G5	Dry	Metal	13.3	4	0 to 1.75	8 to 10
		Diamond	6	4	0	3.75 to 4
		Concrete	7.2	5.7	-1	6
	Wet	Metal	23	4.9	3.5 to 4	9 to 10
		Diamond	7	3.1	1.5	3
		Concrete	18.4	5.4	2.5 to 3	6.5

Table 4. Average Force Summary for all Test Scenarios (Continued)

			Cutting Phase 1		Cutting Phase 2	
Panel Material	Dry/Wet Cuts	Saw Blade Type	Average Peak F_P (lb)	Average Peak F_A (lb)	Average F_P Range (lb)	Average F_A Range (lb)
CF16	Dry	Metal	10	1.9	1	3.5 to 4
		Diamond	4.2	2.9	0 to 0.5	2
		Concrete	5	2.1	-1 to 0	2 to 2.5
	Wet	Metal	12.2	2	2.5 to 3	6
		Diamond	4.8	3	1	1.75 to 2
		Concrete	11	1.6	1 to 1.5	4 to 4.5
CF24	Dry	Metal	11.9	2.3	1-2	7 to 9.5
		Diamond	5.4	3.4	0	3
		Concrete	10.7	2.6	0-1	5.5 to 6.5
	Wet	Metal	N/A	N/A	N/A	N/A
		Diamond	6.3	2.9	1.75	2
		Concrete	14.9	2.9	3	5

4.1.1 Aluminum Panels.

Average force comparisons for aluminum panels are shown in figures A-1 to A-4 in appendix A, and a summary of the forces is shown in table 4. Overall, regarding dry cuts, the concrete saw blade registered the lowest forces of the three saw blades. Although the metal saw blade registered high forces for AL06 panels, the diamond-tipped saw blade registered the highest forces for the AL08 panels of all the saw blades. For the wet cuts, the metal saw blade registered significantly high F_P, while the diamond-tipped saw blade registered the lowest forces for the both thicknesses. Based on these observations, for aluminum panels, it is recommended to use a concrete saw blade for dry cuts, and a diamond-tipped saw blade for wet cuts.

4.1.2 The GLARE Panels.

Average force comparisons for GLARE panels are shown in figures A-5 to A-8 in appendix A, and a summary of the forces is provided in table 4. When comparing the results of both GLARE thicknesses, the metal registered the overall highest F_P and F_A values for both the dry and wet cuts, and the diamond-tipped saw blade registered the lowest values. The concrete saw blades had slightly higher forces than the diamond-tipped saw blade for the dry cuts, but these values were higher during the wet cuts. Because of these findings, a diamond-tipped saw blade is recommended for both dry and wet cutting operations involving GLARE panels. When comparing these force measurements with those for the aluminum panels, the diamond-tipped saw blades exerted less force on the GLARE panels than on the aluminum panels for both dry and wet cuts. The concrete saw blades exerted less force on the GLARE panels than the aluminum panels for dry cuts, but exerted higher peak F_P on the GLARE panels than the aluminum panels. In general, the metal saw blade exerted less force when cutting aluminum panels than it did for the GLARE panels, for both wet and dry cut conditions.

4.1.3 The CFRP Panels.

Average force comparisons for CFRP panels are shown in figures A-9 through A-12 in appendix A, and a summary of the forces is provided in table 4. Similar to the GLARE panel tests, it was determined that the diamond-tipped saw blade was best saw blade for cutting the CFRP panels. Metal saw blades not only had the highest force values, but one suffered a catastrophic failure during the wet cuts due to the magnitude of the high forces. During the dry cuts of the thinner CFRP panels, the concrete saw blade had similar forces to the diamond-tipped saw blade, but had much higher forces when cutting thicker material and in wet conditions. Comparing these results with those from the aluminum tests, the diamond-tipped saw blade cut the CFRP panels much more easily than the aluminum panels. The metal saw blades cut the thinner CFRP panels more easily than the thinner aluminum panels during wet cuts. However, metal saw blades are not recommended for wet cuts to the thicker CFRP panels. Concrete saw blades had mixed results between both materials.

4.2 SAW BLADE WEAR.

The second part of the of the cut rig test analysis entailed evaluating the wear on all saw blades used during the test panel cuts. The evaluations consisted of three different parts: visual inspection, saw blade diameter loss, and saw blade weight loss.

4.2.1 Visual Inspection.

For the visual inspection, saw blades were photographed before and after each test run. Photographs of the uncut saw blades for each saw blade type are provided in appendix B. The photographs show that both concrete and metal abrasive saw blades had a uniform thickness across the saw blades, and both had rough edges on the saw blades. Likewise, the diamond-tipped saw blade had a smooth surface, except on the edge where it was infused with diamond dust. Photographs in appendix C show the conditions of each saw blade after use in each test scenario.

4.2.1.1 Metal Saw Blade.

When examining the metal saw blade wear, those used for dry cutting trials displayed the most amount of wear on the edges. Visible thinning, or sharpening, of the edge was observed in the saw blades used for the dry cuts for both aluminum and CF16 panels. Surface wear (exposed fiber) on the saw blade was visible on the saw blades used for the wet cuts on AL08 and CF16. The lack of surface wear on the saw blades during the dry cutting trials could be because abrasive saw blades are meant to be used to create high heat, making it easier to cut. However, during wet cuts, water cools the panel surface and increases the friction between the saw blade's surface and the panel, which makes cutting more difficult and damages the saw blade. No edge thinning was visible on the saw blades used for wet cutting trials; however, the saw blade used for CF24 broke apart. Figure C-12, in appendix C, shows the damage to this saw blade and the exposed fiber that remained after the metal piece broke off while trying to cut the CFRP panel.

4.2.1.2 Concrete Saw Blade.

Visual inspections showed that concrete saw blades generally had more edge wear for dry cuts than for wet cutting trials. The wear on the concrete saw blades used for dry cutting trials was similar to that for the metal saw blades because visible thinning was observed. On the aluminum test panels, the concrete saw blades showed more visible wear on the surface during the wet cutting trials than the dry cutting trials. In the appendix C figures that show aluminum tests results, observably more fibers are exposed on the concrete saw blades' surface for the wet cutting trials. This type of surface damage was observed again for the concrete saw blade used during the wet cutting trials for G3. Again, this could be due to the nature of abrasive saw blades being used on cooled surfaces. Finally, visual inspections showed that concrete saw blades used for the wet cuts on CFRP panels appeared to have the least amount of wear. This could be because CFRP material has no metal as part of its composition.

4.2.1.3 Diamond-Tipped Saw Blade.

When evaluating the diamond-tipped saw blades, edge wear appeared to be equal under all conditions. The saw blade that displayed the most amount of edge wear was the one used for the dry cuts on the AL08 panel. The saw blades used for wet cuts had more visible surface wear than the other saw blades. This could be because the surfaces were cooled, and the materials could not be softened.

4.2.2 Saw Blade Weight Loss.

Saw blade weight loss was calculated by weighing each saw blade before and after each cutting trial. Saw blades used on the wet cutting trials were air dried before being weighed after cutting. All saw blade weight comparisons are provided in appendix D. Some cutting trials did not have a full 24-cut series due to either the saw blade breaking or the cut rig binding up from too much force exertion. Because the cutting trials were not completed for these saw blades, they were not included in the percentage saw blade weight loss evaluations. Figures 12 and 13 show the percentage saw blade weight loss for the dry runs and wet runs, respectively. Figure 12 shows that the most loss in saw blade weight for dry trial runs occurred during the aluminum panel trials, in which the concrete saw blades had the highest percentage of weight loss. The concrete saw blade lost more weight during the cutting trials for the thinner aluminum and CFRP panels than for their thicker counterparts. However, the concrete saw blade lost more weight during the cutting trials for the thicker GLARE panel than for the thinner panel. Metal saw blades had similar saw blade weight loss for the aluminum cuts and barely any loss for the composite cuts. The diamond-tipped saw blades exhibited minimal saw blade weight loss for all dry cutting trials. Saw blade weight loss was significantly reduced in wet conditions, as shown in figure 13. Again, the concrete saw blades had the most saw blade weight loss, and again, it was mostly during the aluminum cutting trials. The concrete saw blade lost more weight cutting the thinner aluminum than the thicker panel. It had minimal loss for the rest of the material panels. The metal and diamond-tipped saw blades barely lost any weight during the wet cutting trials. Overall, the diamond-tipped saw blade exhibited the least saw blade weight loss, while the concrete saw blades exhibited the most saw blade weight loss, especially during the dry cutting trials.

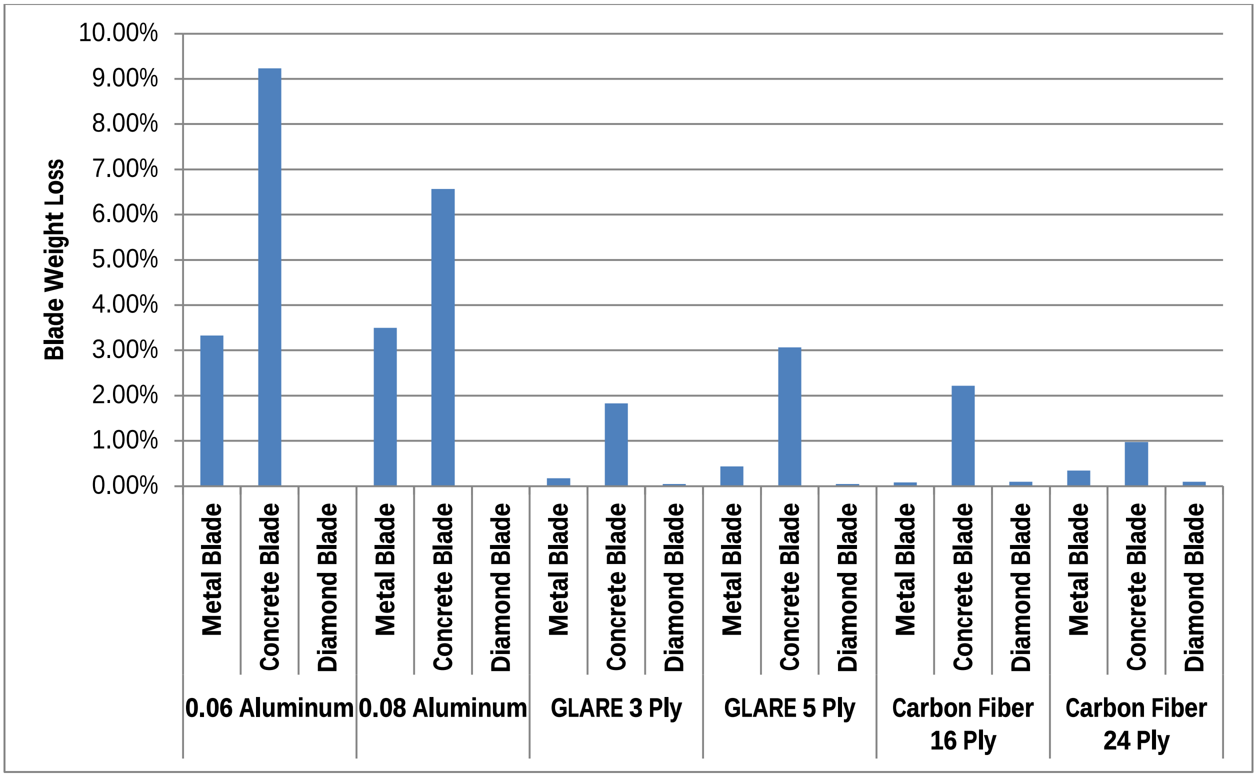

Figure 12. Saw Blade Weight Loss for Dry Cuts

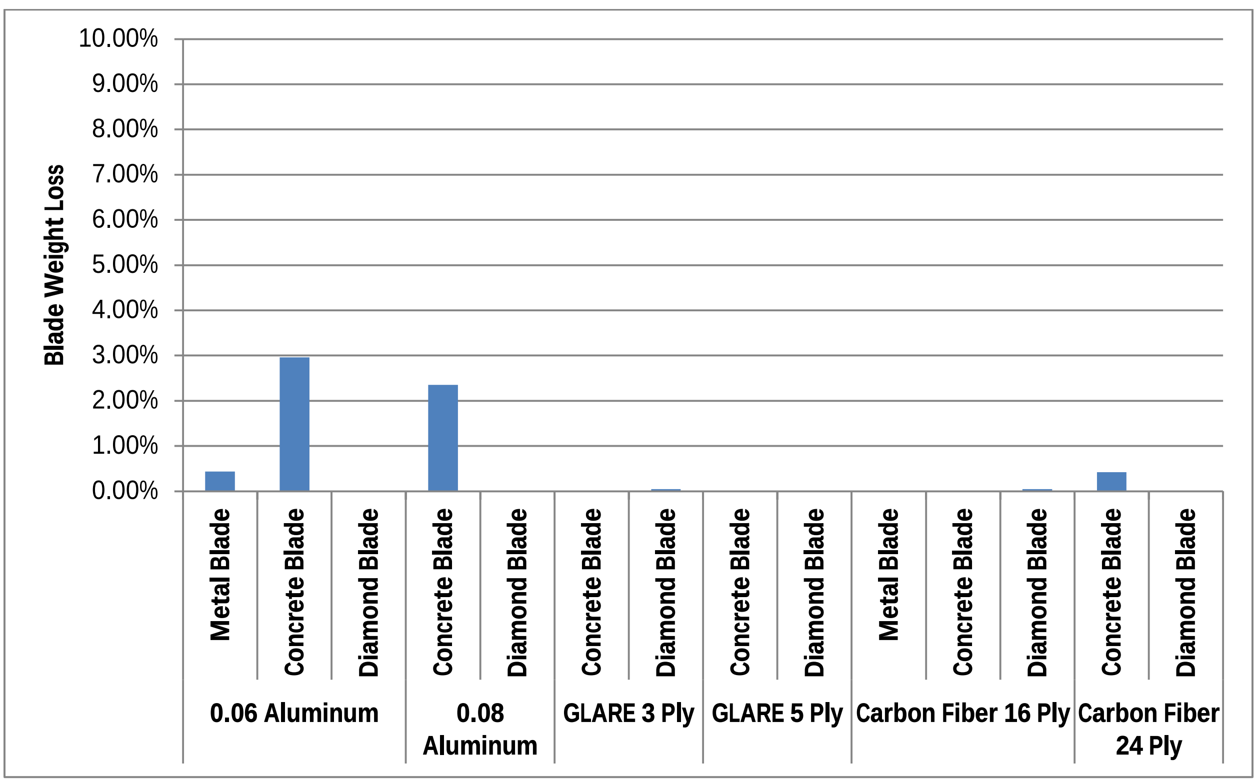

Figure 13. Saw Blade Weight Loss for Wet Cuts

4.2.3 Saw Blade Diameter Loss.

Saw blade diameter loss was recorded by measuring the saw blade diameters before and after each test run. The diameter measurements for each saw blade can be found in appendix D. Saw blades that did not complete a full cut series were not included in this evaluation. Figures 14 and 15 show the percentage of saw blade diameter loss for the dry and wet runs, respectively. As the figures show, the concrete saw blades exhibited the most diameter loss than any of the other saw blades. When comparing diameter loss in different materials, the concrete saw blades lost more when cutting the aluminum panels than the composite panels. The metal saw blades lost more diameter length with the aluminum cuts but barely lost diameter length with the composites. The diamond-tipped saw blades did not lose diameter length in any dry cutting trials, but this could be due to the nature of the saw blade's metal composition. For the wet cutting trials, the diameter length loss was less for the concrete saw blades; however, the metal and diamond-tipped saw blades used for the wet cutting trials exhibited no diameter length loss. Overall, the concrete saw blade lost the most diameter length, and the diamond-tipped saw blades did not lose any.

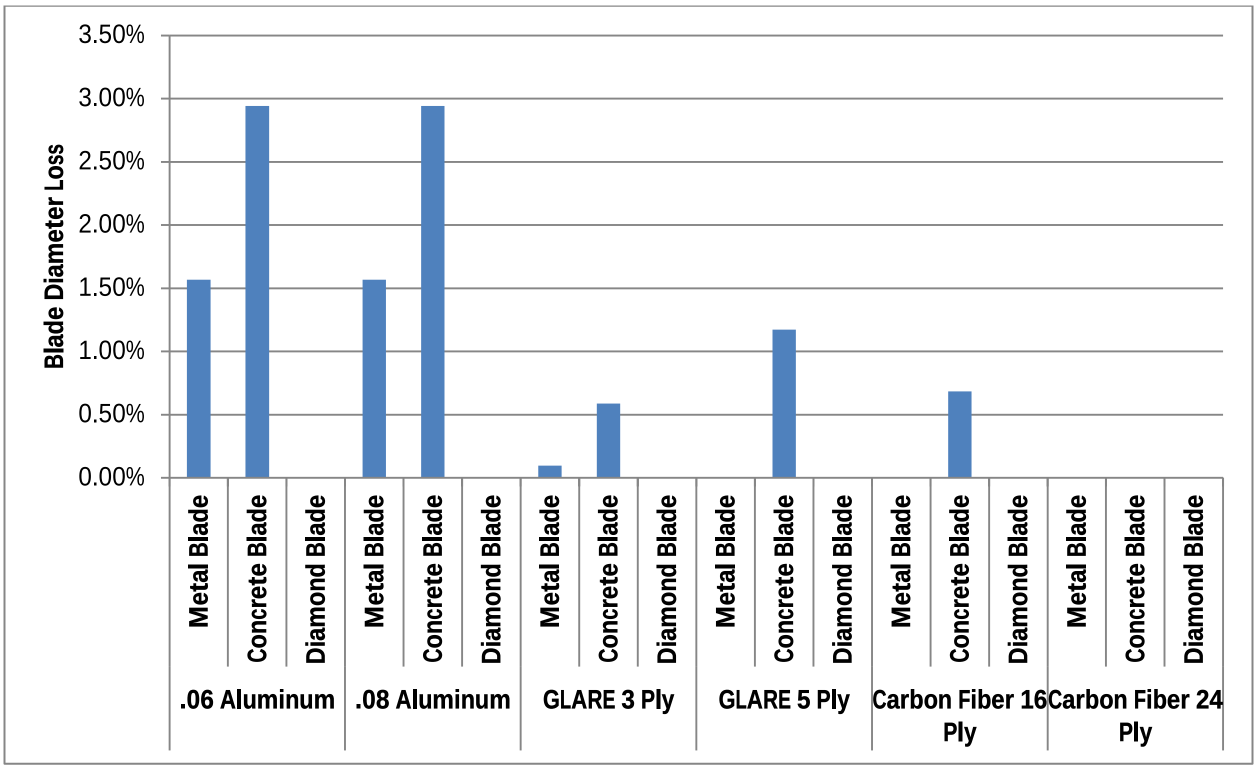

Figure 14. Saw Blade Diameter Loss for Dry Cuts

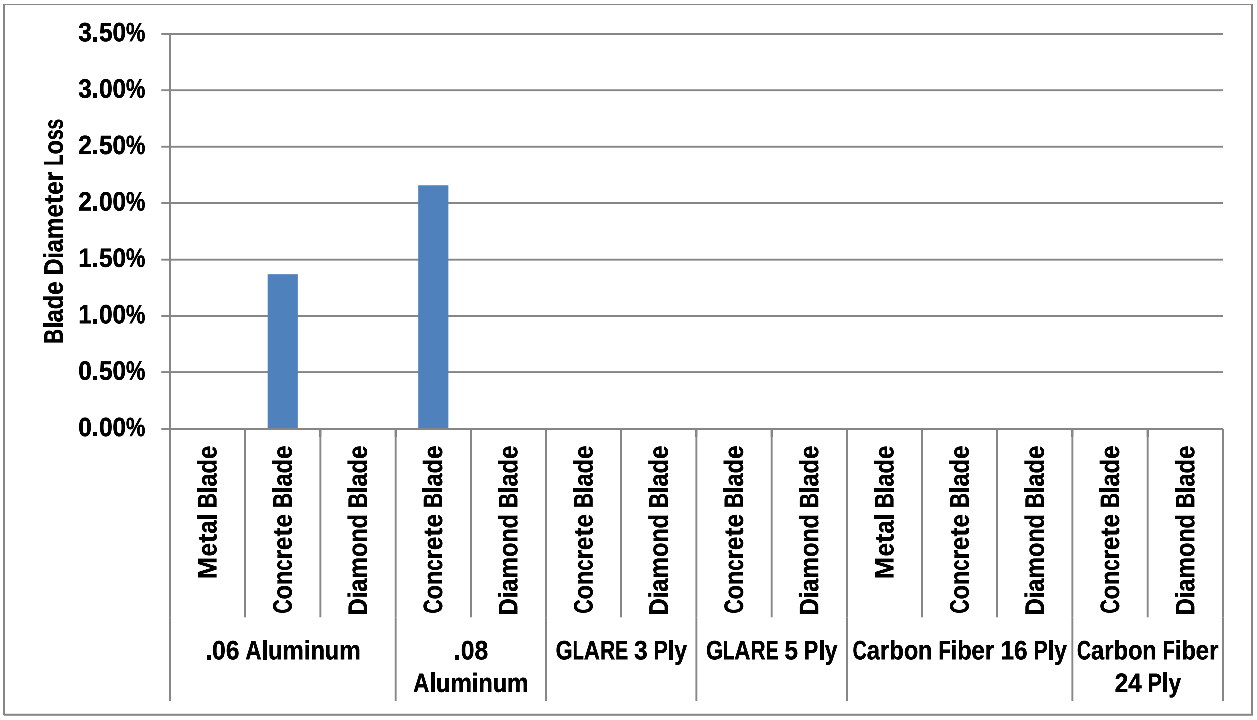

Figure 15. Saw Blade Diameter Loss for Wet Cuts

4.3 PARTICULATE ANALYSIS.

Respiratory hazards were assessed during the saw blade evaluations. The William J Hughes Technical Center Safety Office (Safety Office) collected integrated air samples during certain cut rig trial runs using the particulate sample collectors inside the cut rig enclosure. Monitoring for exposure to respirable particulates, carbon nanotubes, and nanofibers was notably important, as there is a lack of previous studies available that document exposure effects from cutting into carbon fiber composite aircraft skin. Over the course of four days of saw blade testing, the Safety Office collected air samples for analysis using the following methods [9]:

- Respirable particulates, National Institute for Occupational Safety and Health (NIOSH) 0600
- Elemental carbon, NIOSH 5040
- Glass fiber, NIOSH 7400B
- Carbon fiber, NIOSH 7402 modified for carbon fiber

All samples were analyzed at Bureau Veritas North America, Inc. Laboratories, which is accredited by the American Industrial Hygiene Association. The assessment method for exposure to carbon nanotubes and carbon nanofibers was taken from the Centers for Disease Control and Prevention, NIOSH Current Intelligence Bulletin 65, "Occupational Exposure to Carbon Nanotubes and Nanofibers," dated April 2013 [10]. This method included samples for elemental carbon with additional samples for carbon fiber using transmission electron microscopy. Results are summarized in tables 5 through 8 [9]. Graphic representations of these results are provided in appendix E.

Table 5. Respirable Particulates, NIOSH 0600 [9]

Test	Raw Concentration for 1-Hour Sample	8-Hour Time Weighted Average	OSHA 8-Hour Permissible Exposure Level
Metal saw blade, GLARE	4.3 mg/m3	0.54 mg/3	5.0 mg/m3
Concrete saw blade, GLARE	4.1 mg/m3	0.51 mg/m3	5.0 mg/m3
Diamond-tipped saw blade, GLARE	1.5 mg/m3	0.19 mg/m3	5.0 mg/m3
Metal saw blade, carbon fiber	23 mg/m3	2.88 mg/m3	5.0 mg/m3
Concrete saw blade, carbon fiber	24 mg/m3	3.00 mg/m3	5.0 mg/m3
Diamond-tipped saw blade, carbon fiber	17 mg/m3	2.13 mg/m3	5.0 mg/m3

Table 6. Elemental Carbon, NIOSH 5040 [9]

Test	Raw Concentration for 1-Hour Sample	8-Hour Time Weighted Average	NIOSH 8-Hour Recommended Exposure Limit
Metal saw blade, carbon fiber	10 mg/m3	1.25 mg/m3	0.001 mg/m3
Concrete saw blade, carbon fiber	8.8 mg/m3	1.1 mg/m3	0.001 mg/m3
Diamond-tipped saw blade, carbon fiber	5.6 mg/m3	0.70 mg/m3	0.001 mg/m3

Table 7. Glass Fiber, NIOSH 7400B [9]

Test	Raw Concentration for Sample Time	8-Hour Time Weighted Average	NIOSH 8-Hour Recommended Exposure Limit
Metal saw blade, GLARE	0.21 fibers/cc	0.03 fibers/cc	3 fibers/cc
Concrete saw blade, GLARE	<0.15 fibers/cc	n/a	3 fibers/cc
Diamond-tipped saw blade, GLARE	<0.18 fibers/cc	n/a	3 fibers/cc

Table 8. Carbon Fiber, NIOSH 7402 Modified for Carbon Fiber [9]

Test	Raw Fiber Concentration for Sample Time	Mass Concentration of Carbon Fibers	Mass Concentration of Elemental Carbon in Corresponding Sample
Metal saw blade, carbon fiber	3.2 fibers/cc	1.6 mg/m3	10 mg/m3
Concrete saw blade, carbon fiber	7.9 fibers/cc	11 mg/m3	8.8 mg/m3
Diamond-tipped saw blade, carbon fiber	7.5 fibers/cc	5.6 mg/m3	5.6 mg/m3

In general, the carbon fiber composite generated much more respirable particulates than the GLARE composite. In every carbon fiber test with analysis for elemental carbon, real-time concentrations and time-weighted averages of total elemental carbon (not respirable) exceeded the NIOSH recommended exposure limits for respirable elemental carbon. The exposure limits were so high that the only level of adequate respiratory protection would have been a full-face, self-contained breathing apparatus (SCBA) with an assigned protection factor of 10,000. There are currently no recommended exposure levels to carbon fiber. NIOSH recommends assessing exposure to carbon fiber expressed in concentrations of elemental carbon.

Another result from the air sampling from these tests was that in an equal environment, the diamond-tipped saw blade contributed less to the carbon fiber/carbon nanotube exposure than the metal or concrete saw blades. This was determined based on the measured concentration of elemental carbon being equal to the measured mass concentration of carbon fiber.

5. SUMMARY.

In summary, the FAA sought to provide guidance regarding forcible entry via circular saw on aircraft that are composed of mostly aircraft-grade composites. When the practical trials did not provide enough data and could not be considered statistically reliable, the ATRD team developed a cutting trial apparatus and procedure that measured forces exerted by a saw blade on a panel, saw blade wear, and particulate production. Tests examined the performances of three types of saw blades, metal, concrete, and diamond-tipped, on cutting panels of various thicknesses of aluminum, GLARE, and CFRP. Tests also assessed the saw blade cutting performance in both dry and wet conditions.

For the aluminum dry cuts, the concrete saw blade produced the lowest amount of force when combining the performances of the saw blades for both thicknesses. For the aluminum wet cuts, the diamond-tipped saw blade exerted the lowest force. When combining both the wet and dry cuts for aluminum panels, the metal saw blade had the worst performance. Of all the saw blades, the metal saw blade registered the highest measured forces it came to cutting GLARE panels. Conversely, the diamond-tipped saw blade exerted the lowest measured forces on both the GLARE dry and wet cuts. The metal saw blade also exerted the highest forces of the three saw blades when cutting CFRP panels; and the saw blade broke when cutting a CF24 panel. Again, the diamond-tipped saw blade exerted the lowest forces for both GLARE dry and wet cuts.

When comparing the force measurements from all panels and all saw blade types, the diamond-tipped saw blade cut through both the GLARE and CFRP panels more easily than the aluminum panels. The metal and concrete saw blades had the highest forces when it came to wet cuts for all three materials. The metal saw blade exerted the most forces of all the saw blades.

Saw blade thinning was more apparent during dry cuts than during wet cuts for both the metal and concrete saw blades. Surface saw blade wear was more apparent for all saw blade types during wet cuts. Mass and diameter loss were more apparent during the dry cuts than the wets cuts. Of the three saw blades, the concrete saw blades had the most mass and diameter loss.

Particulate analysis showed that the diamond-tipped saw blade released the smallest amount of nanoparticulates of the three saw blade types.

Overall, the diamond-tipped saw blade exerted the least amount of force when combining all the force measurements, showed the least amount of wear, and released the least quantity of particulates, concluding it to be the best saw blade type to use on composite materials.

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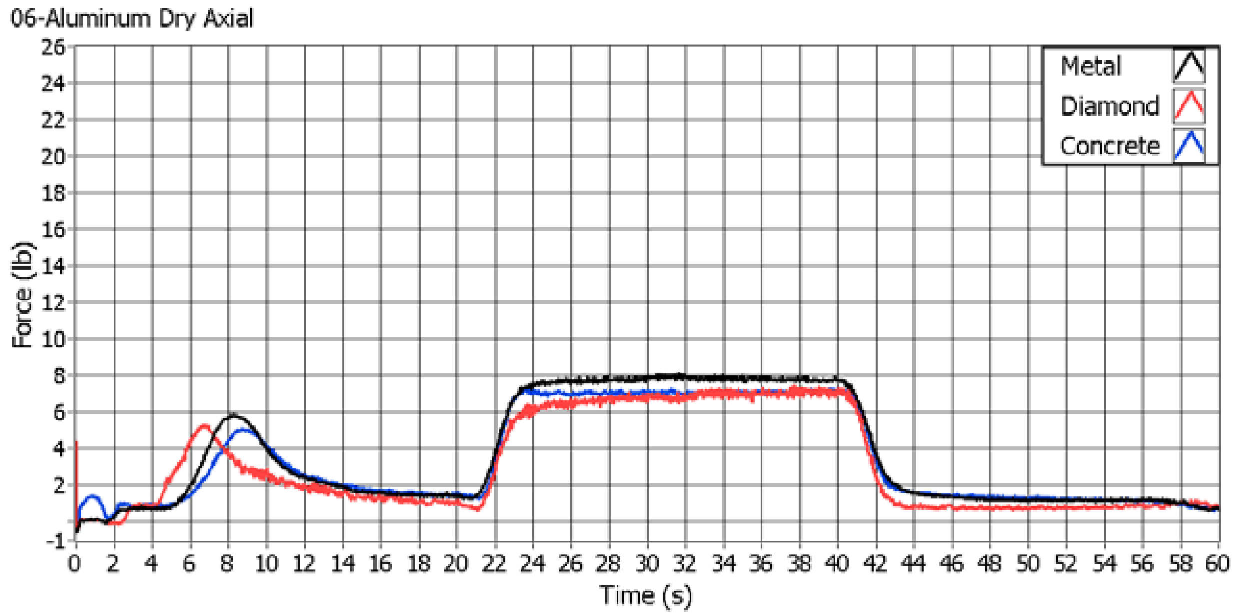
9. Shara, J., “FW: Test Results.” Email message to the author of this report. January 16, 2015.

10. Center of Disease Control and Prevention, Current Intelligence Bulletin 65, “Occupational Exposure to Carbon Nanotubes and Nanofibers,” Cincinnati, Ohio, April 2013.

APPENDIX A—AVERAGE CUT FORCES FROM CUT RIG TRIALS

Figures A-1 through A-12 show the average force comparisons for metal, concrete, and diamond-tipped saw blade types when cutting different thickness panels of aluminum (AL06 and AL08), GLAss-Reinforced aluminum laminate (GLARE), and carbon fiber-reinforced plastic (CFRP) composite materials in both dry and wet conditions. Note, thickness is indicated for GLARE by the number of layers preceded by the letter G, and thickness is indicated for CFRP panels by the number of plies preceded by the letters CF.



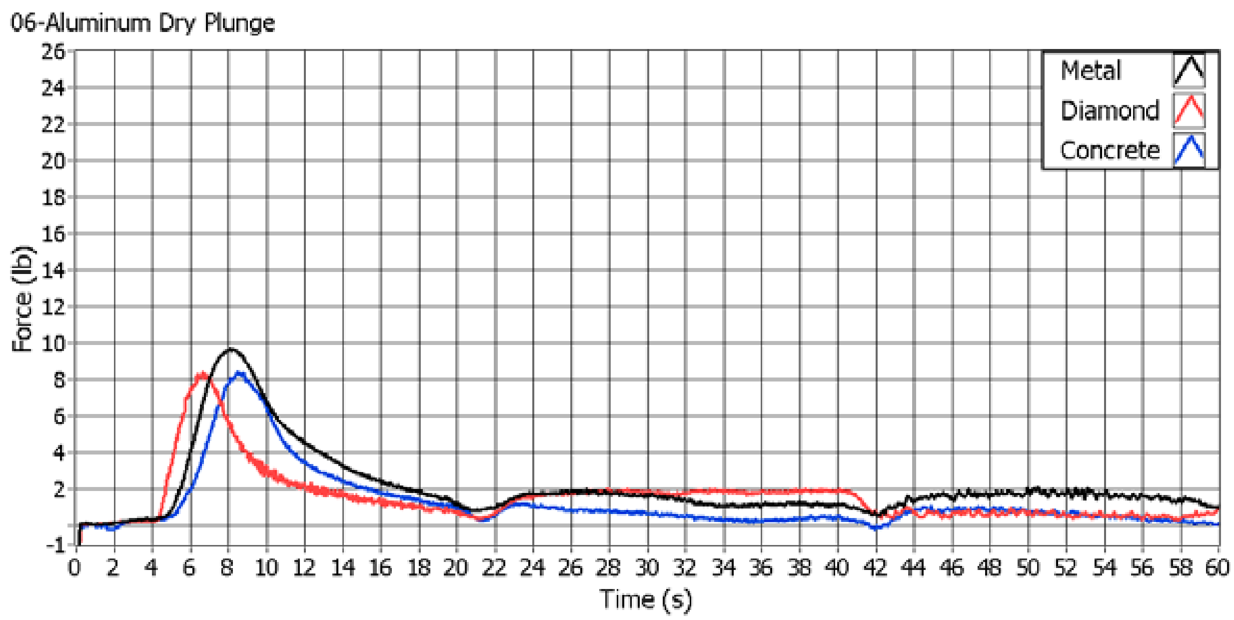
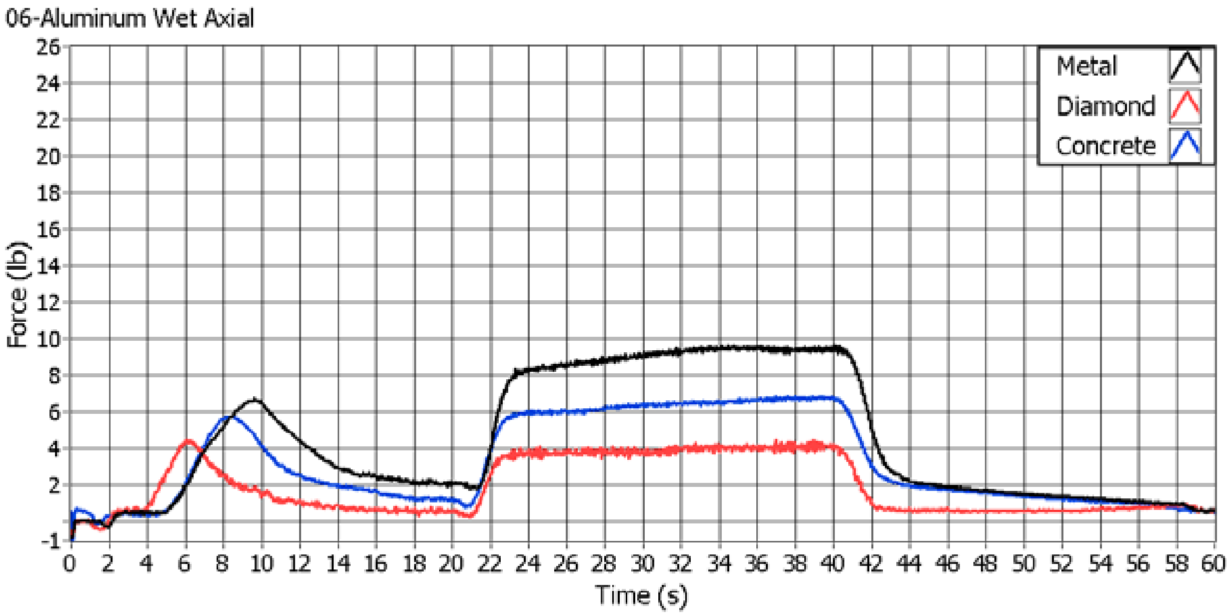


Figure A-1. Average Force Measurements for AL06 Dry Cuts



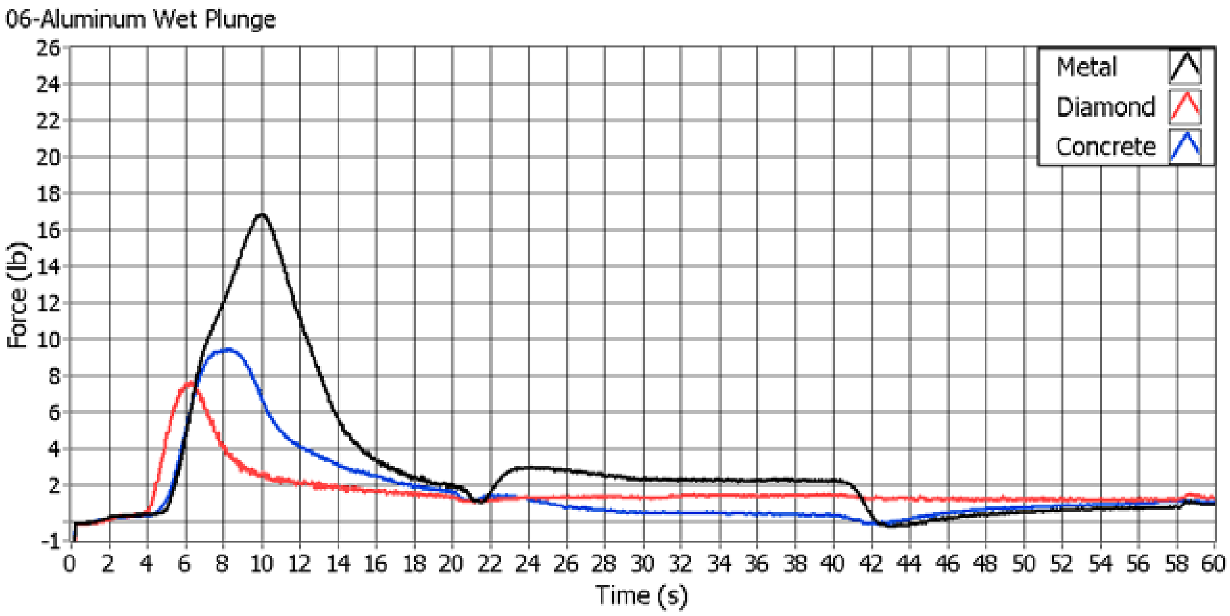


Figure A-2. Average Force Measurements for AL06 Wet Cuts

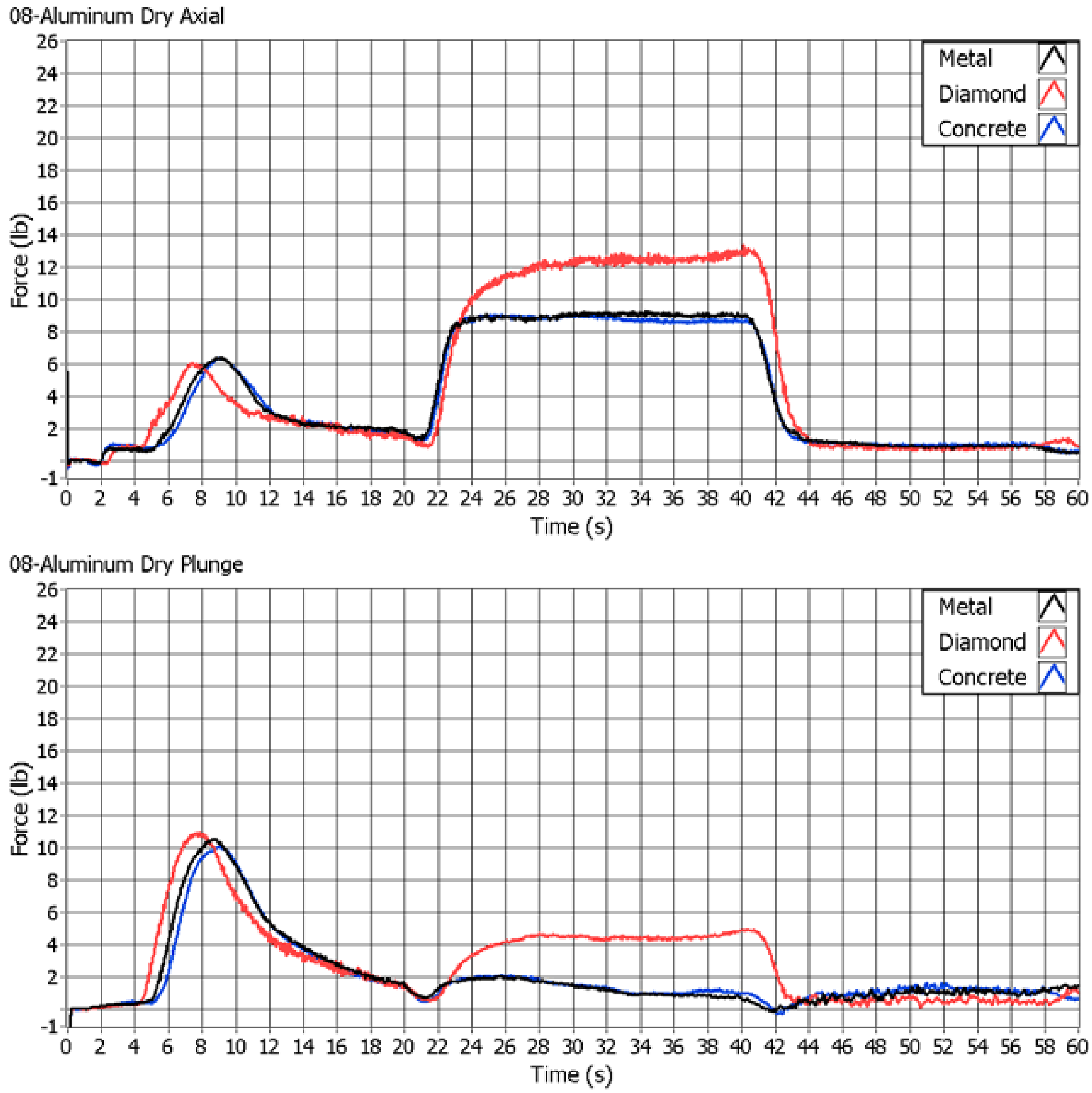


Figure A-3. Average Force Measurements for AL08 Dry Cuts

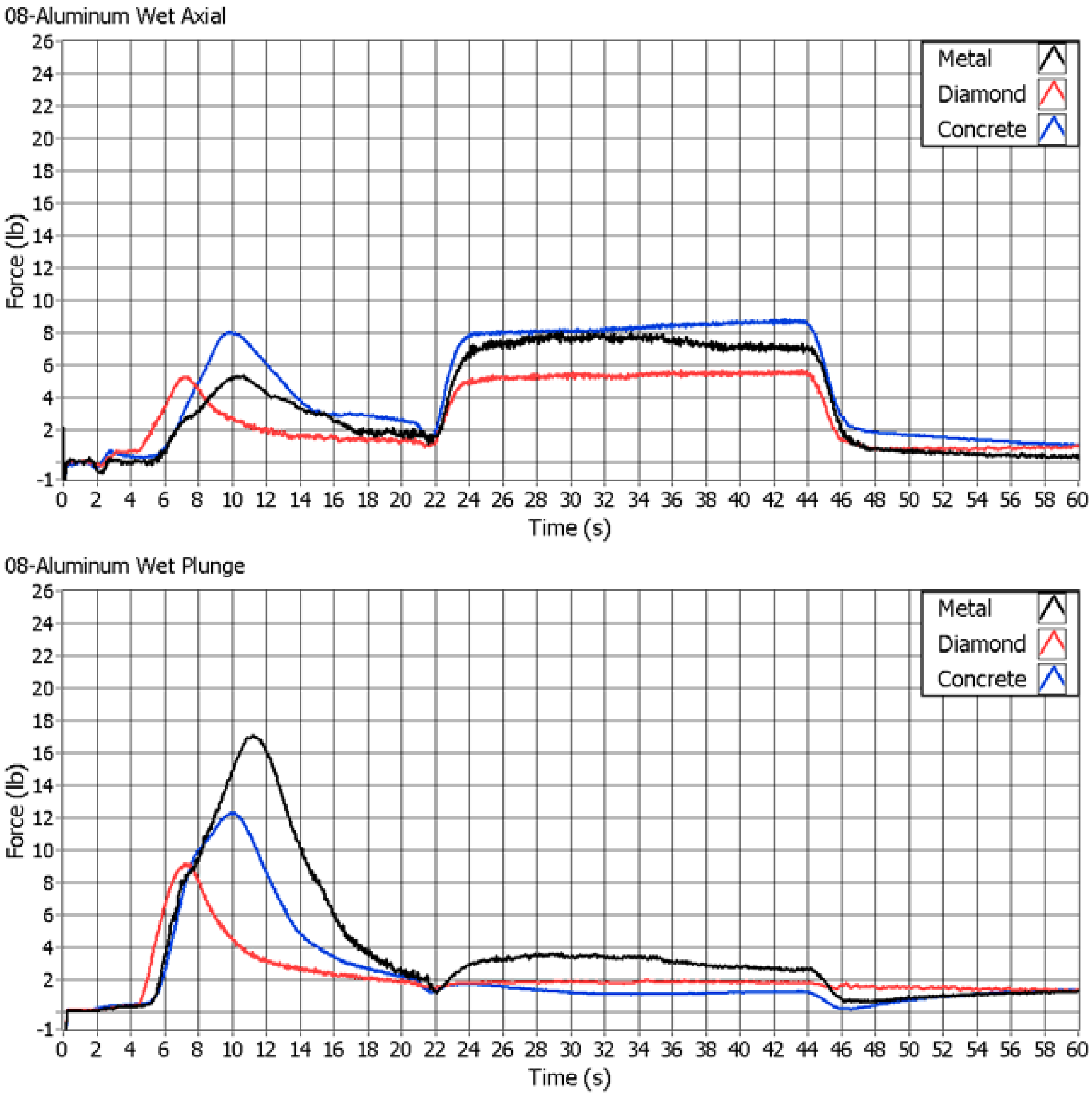
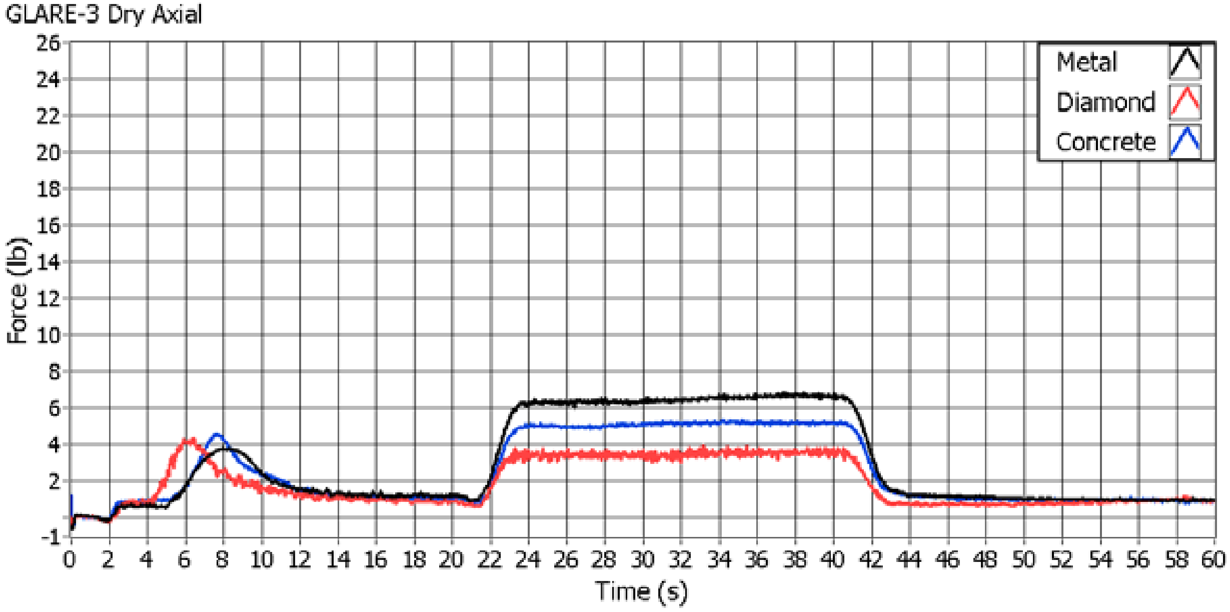


Figure A-4. Average Force Measurements for AL08 Wet Cuts



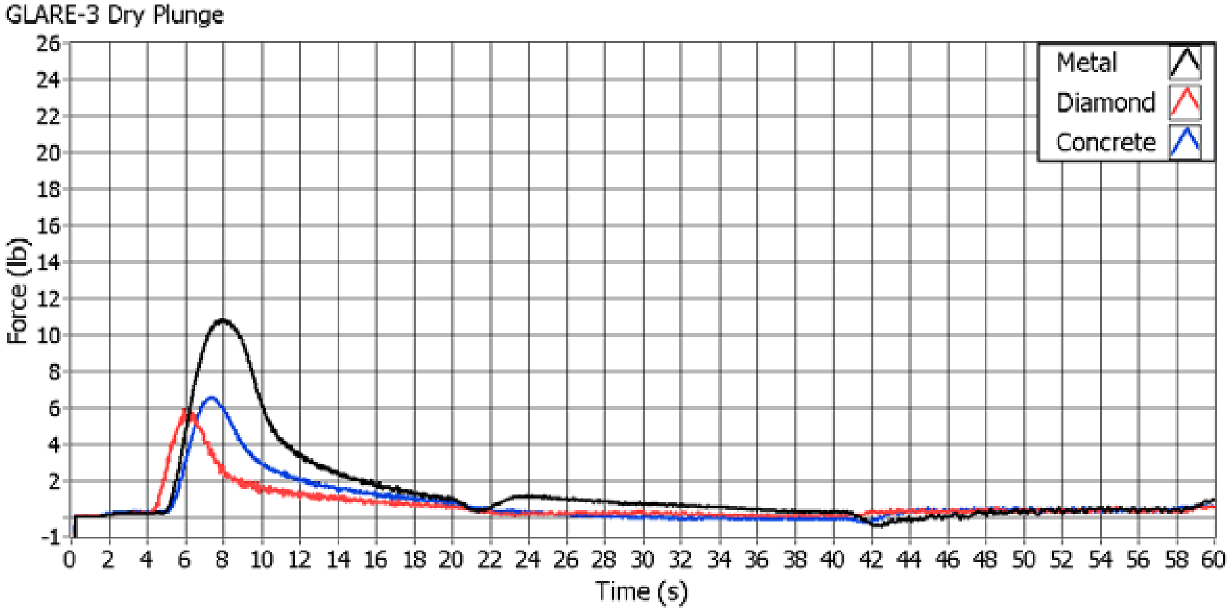
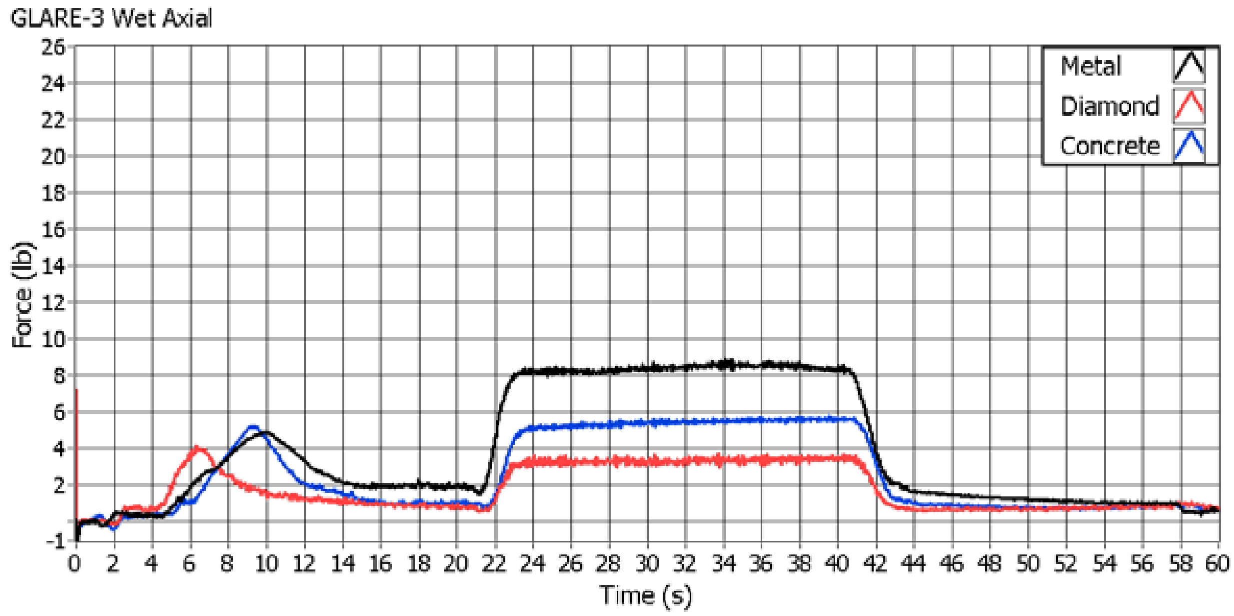


Figure A-5. Average Force Measurements for G3 Dry Cuts



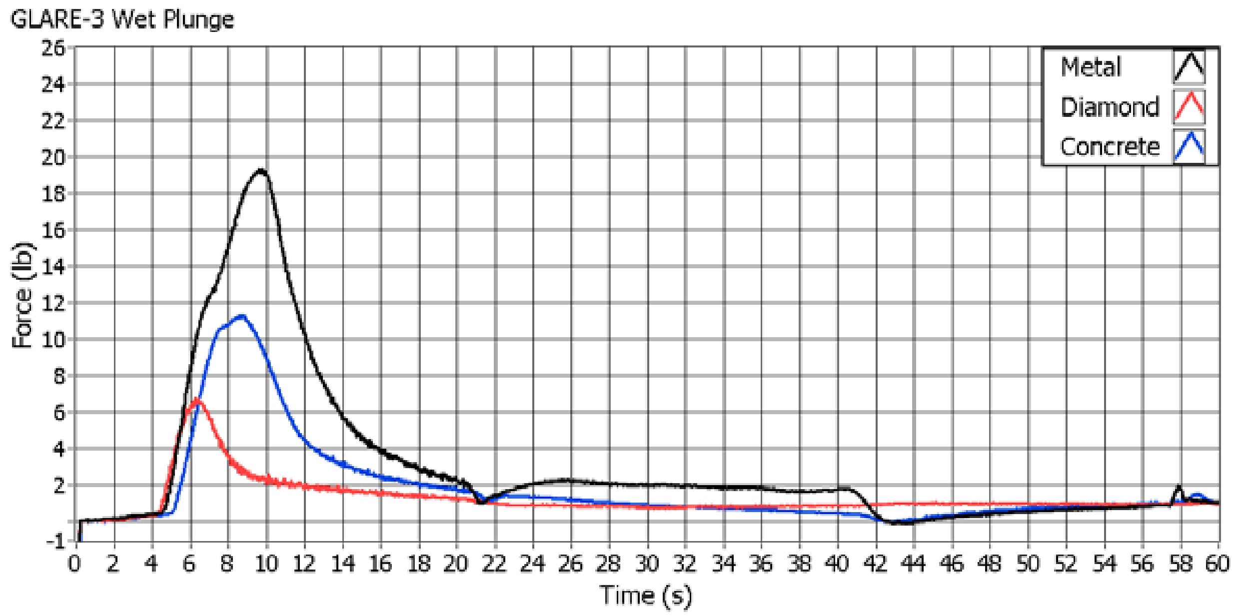


Figure A-6. Average Force Measurements for G3 Wet Cuts

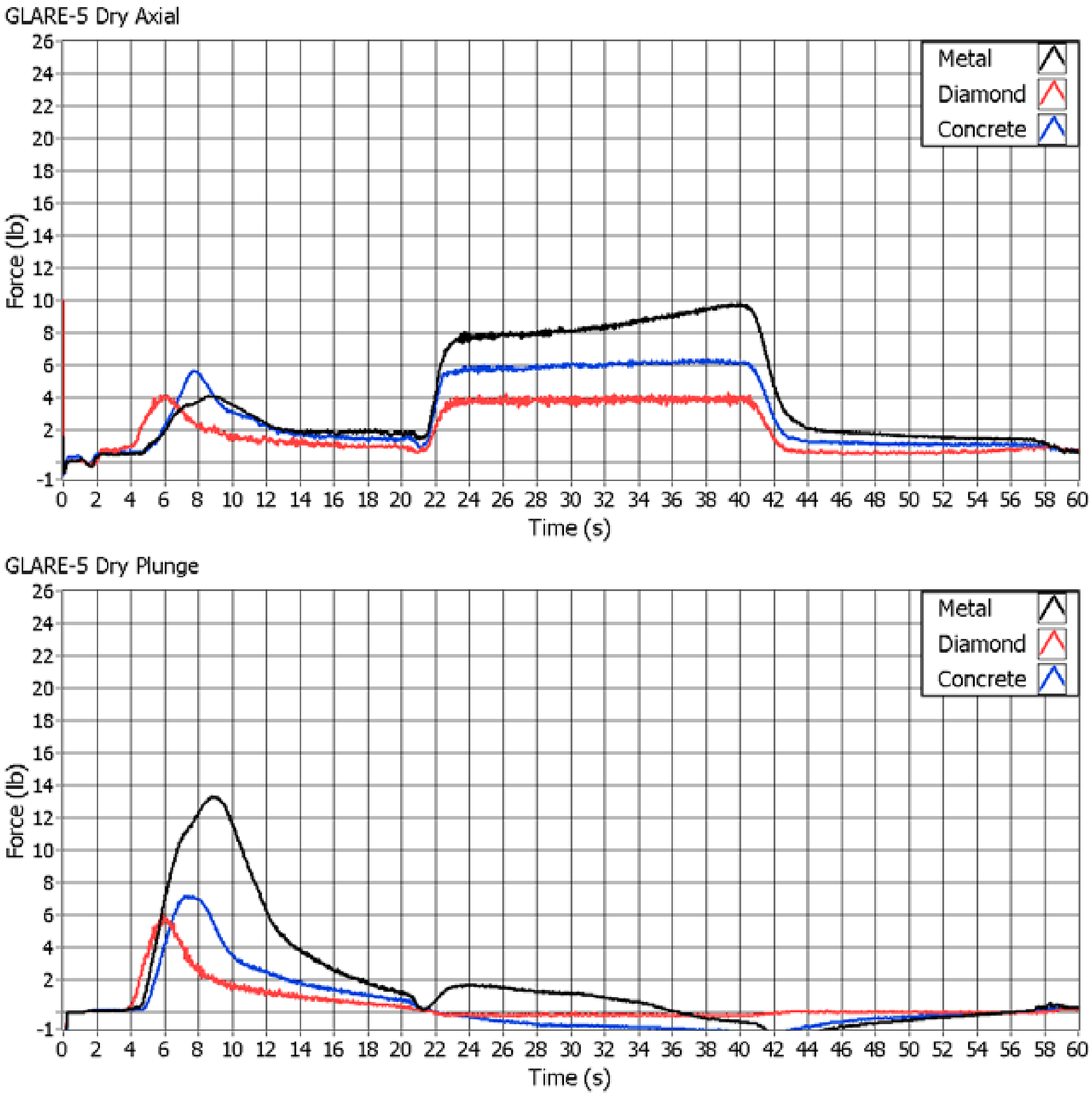
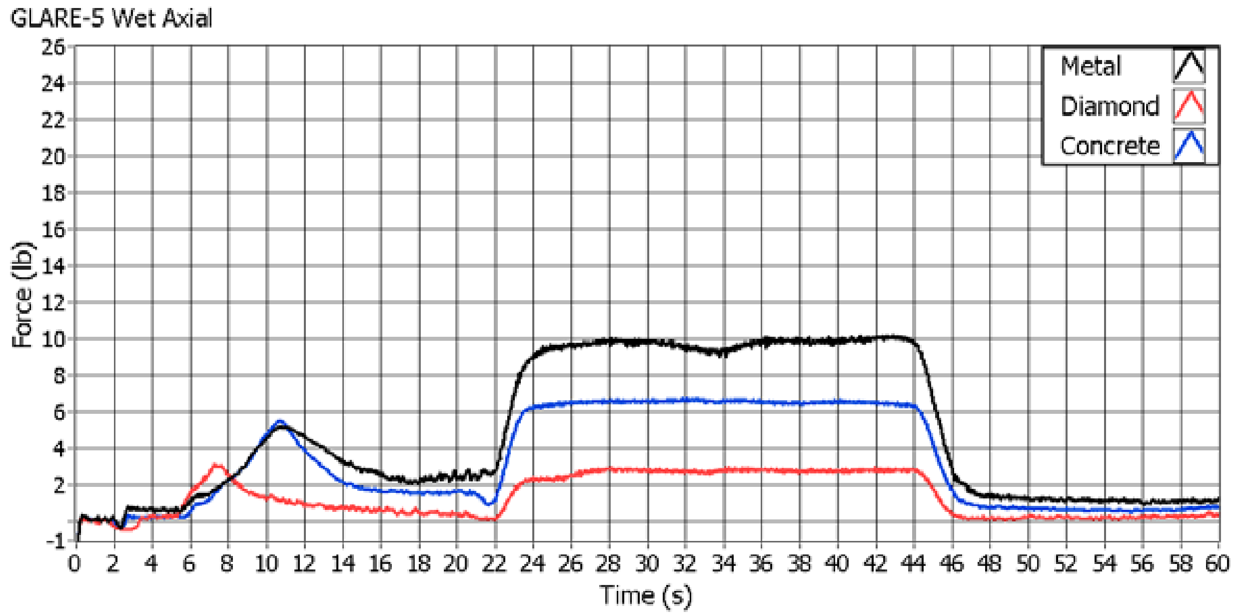


Figure A-7. Average Force Measurements for G5 Dry Cuts



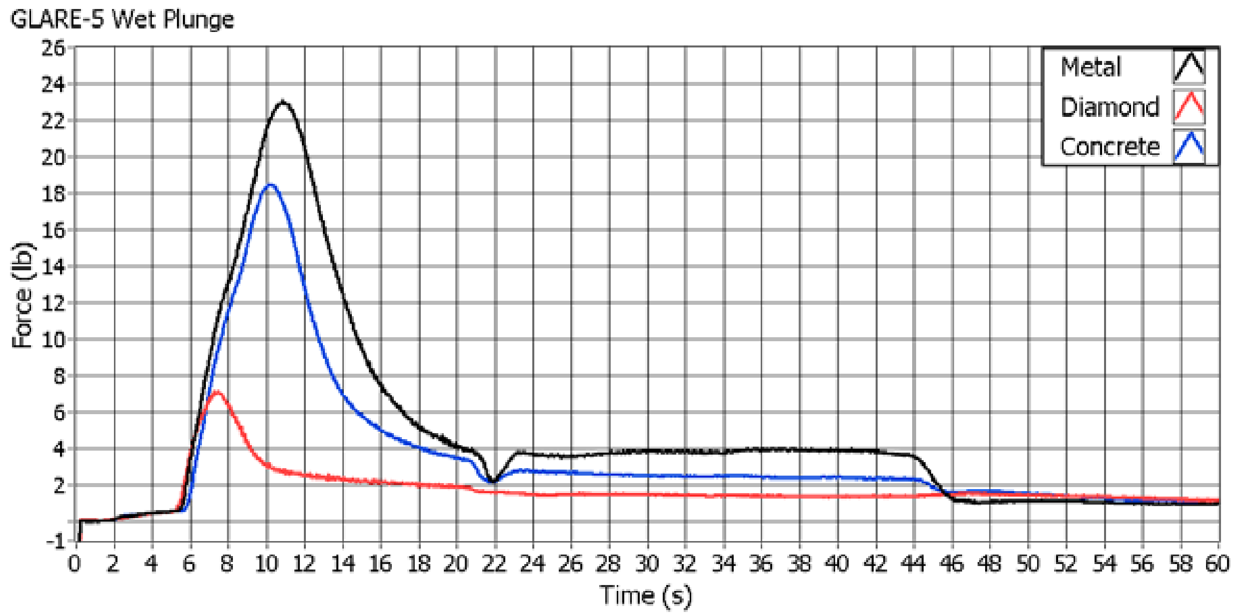


Figure A-8. Average Force Measurements for G5 Wet Cuts

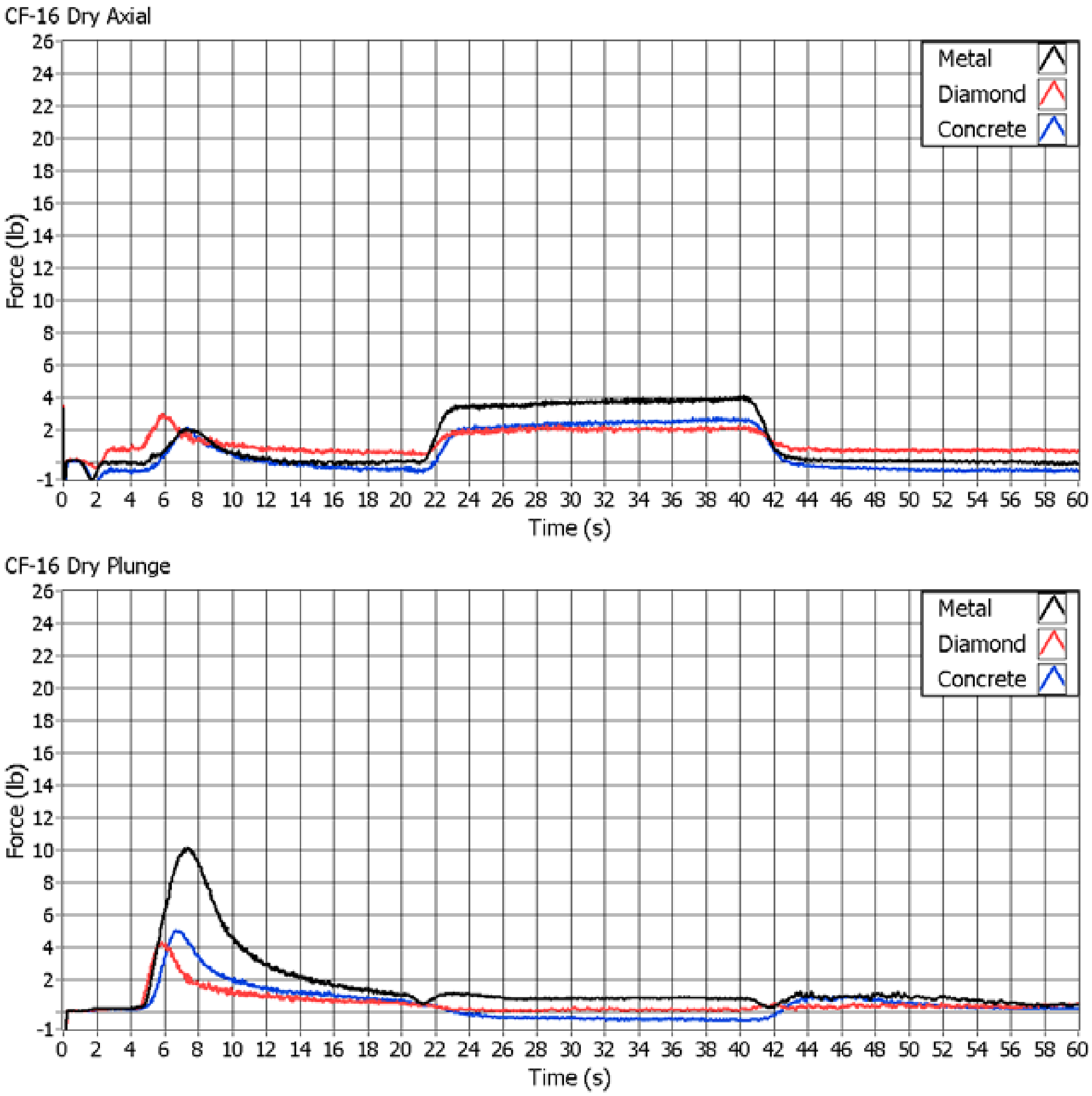
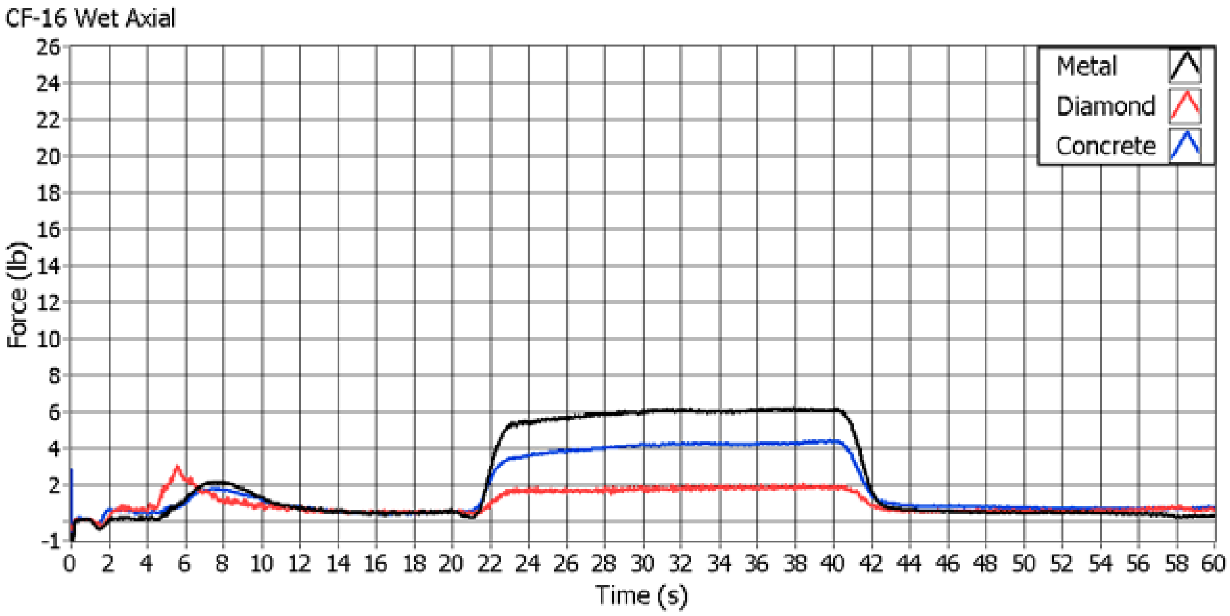


Figure A-9. Average Force Measurements for CF16 Dry Cuts



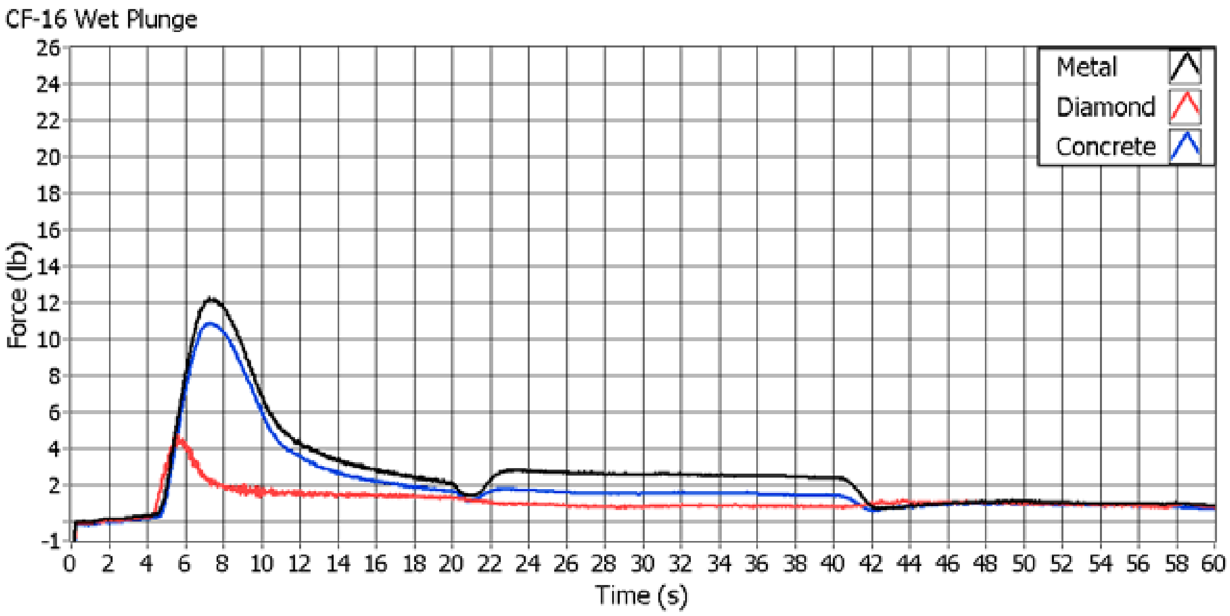
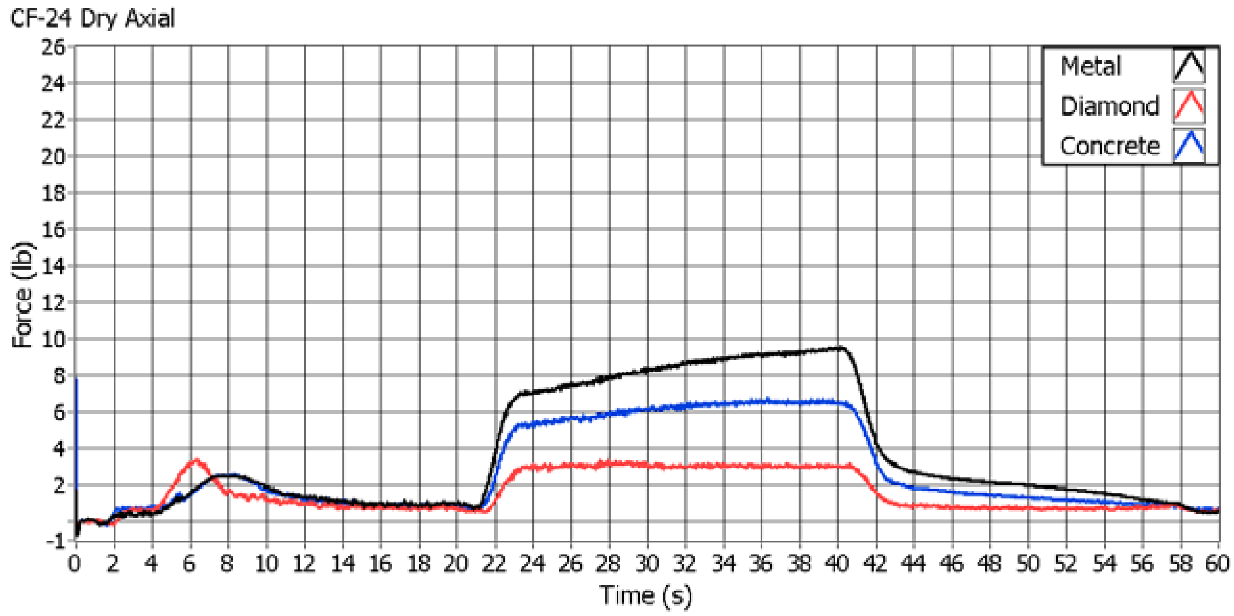


Figure A-10. Average Force Measurements for CF16 Wet Cuts



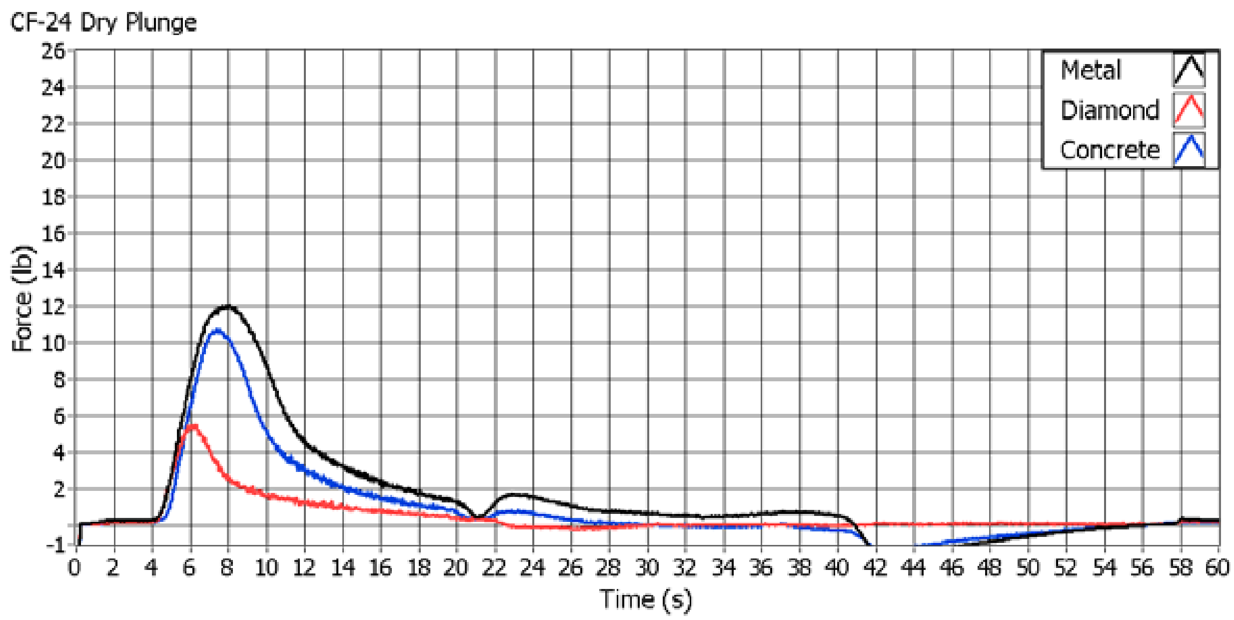


Figure A-11. Average Force Measurements for CF24 Dry Cuts

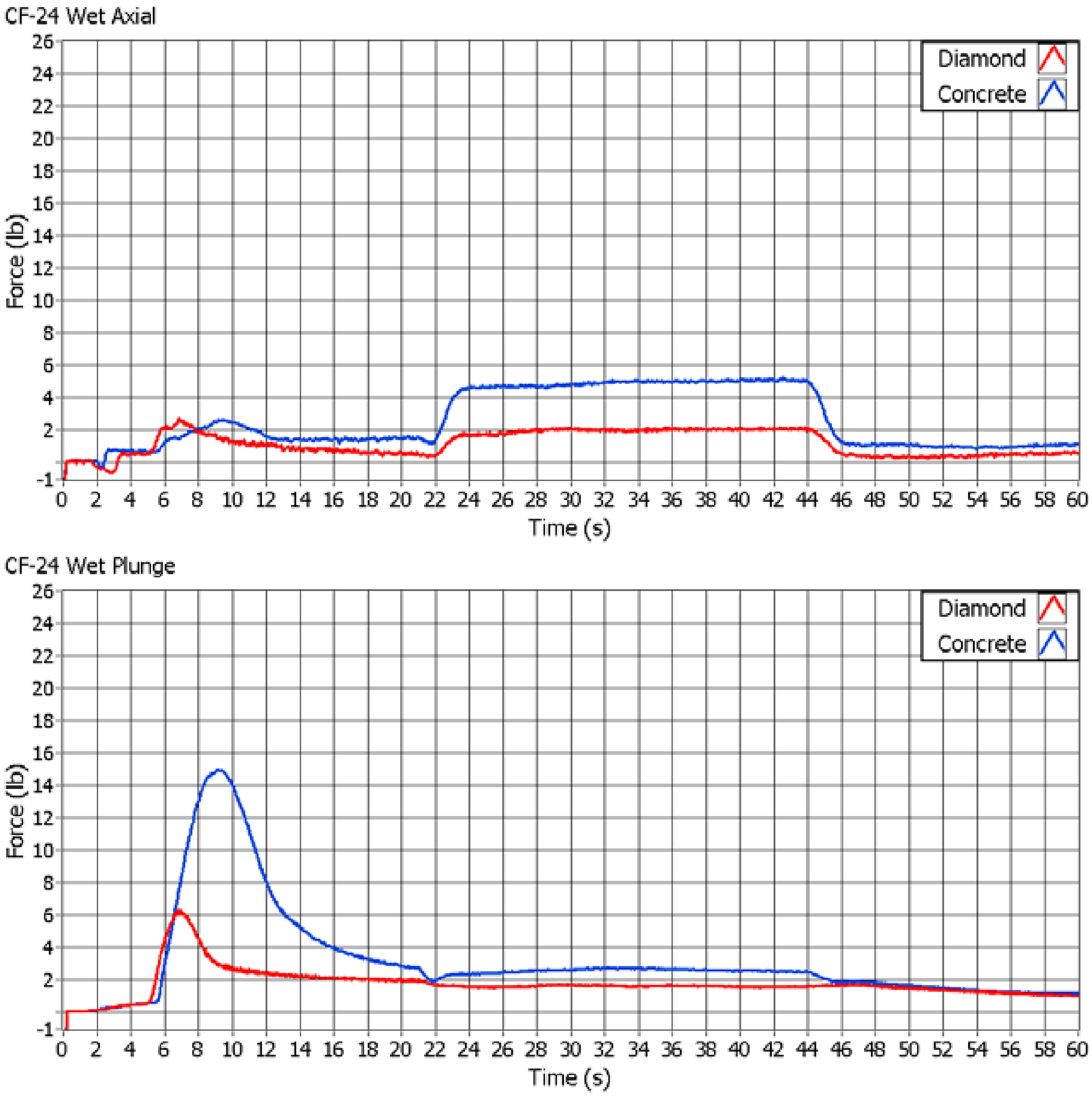


Figure A-12. Average Force Measurements for CF24 Dry Cuts

APPENDIX B—PRETEST SAW BLADE PHOTOGRAPHS

Figures B-1 through B-3 show the pretest photographs of the metal, concrete, and diamond-tipped saw blade types used in this research effort. The top section of each figure shows the surface of each saw blade type without any wear. The bottom section of each figure shows what the unworn edge of each saw blade type looks like.

Figure B-1. Metal Saw Blade, Pretest

Figure B-2. Concrete Saw Blade, Pretest

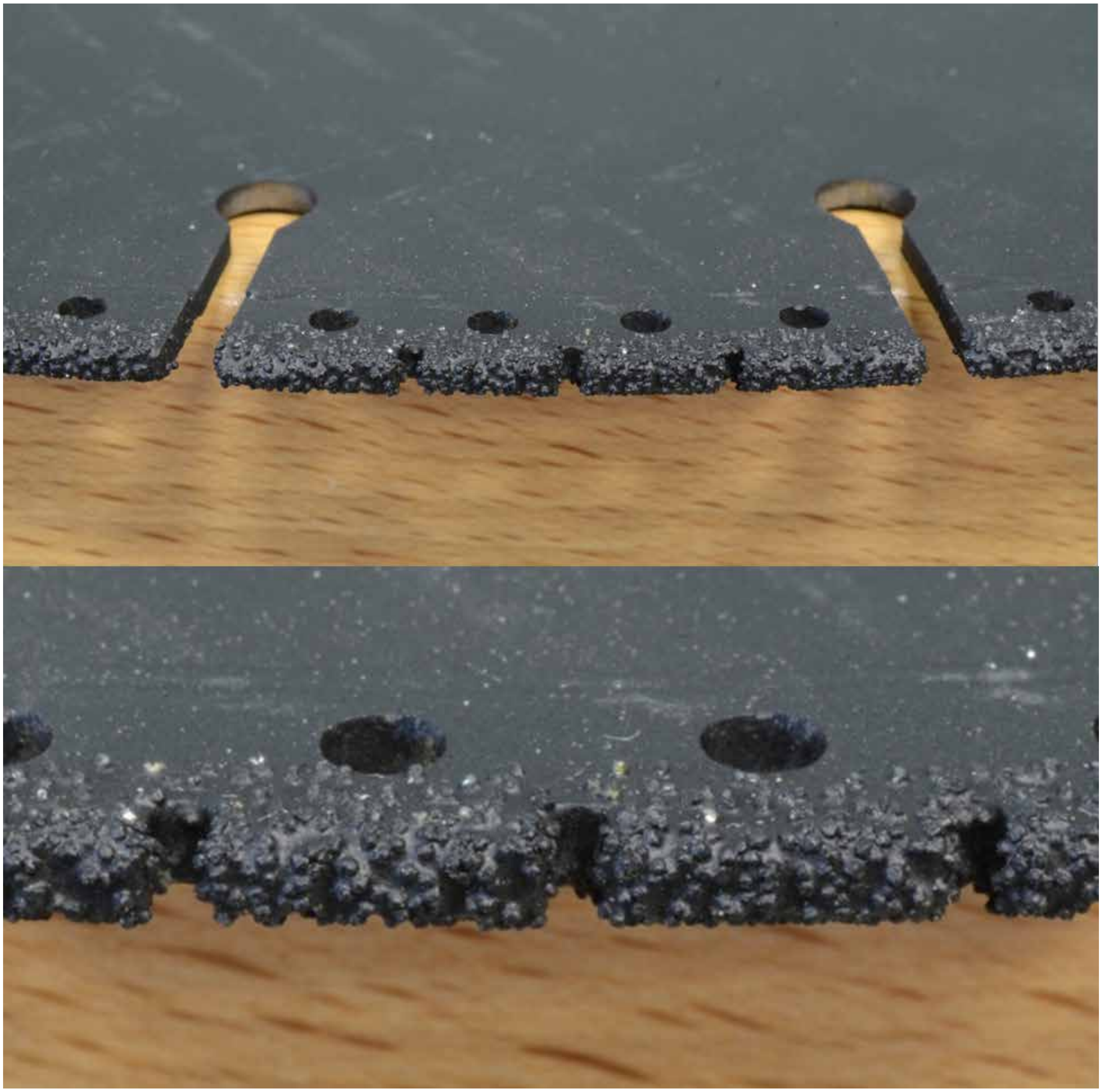


Figure B-3. Diamond Saw Blade, Pretest

APPENDIX C—POSTTEST SAW BLADE PHOTOGRAPHS

Figures C-1 through C-36 show the posttest photographs of the metal, concrete, and diamond-tipped saw blade types when cutting different thickness panels of aluminum (AL06 and AL08), GLAss-REinforced aluminum laminate (GLARE), and carbon fiber-reinforced plastic (CFRP) composite materials in both dry and wet conditions. Note, thickness is indicated for GLARE by the number of layers preceded by the letter G; thickness is indicated for the CFRP panels by the number of plies preceded by the letters CF.

Figure C-1. Metal Saw Blade, AL06, Dry Cuts

Figure C-2. Metal Saw Blade, AL06, Wet Cuts

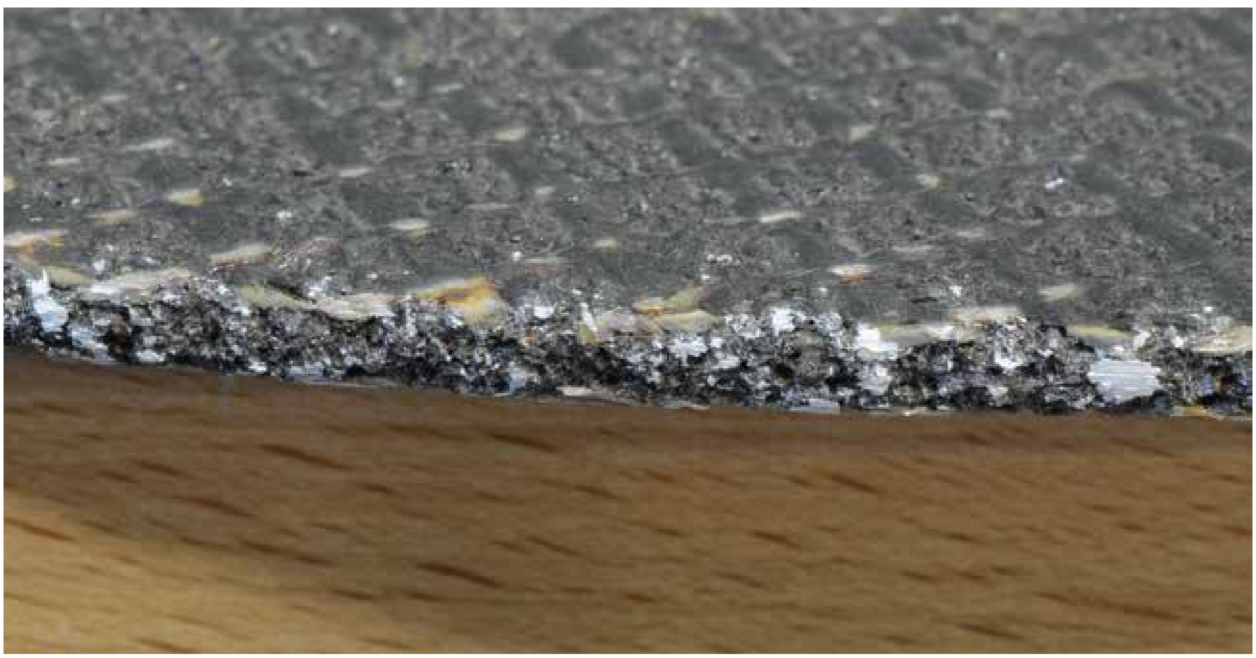


Figure C-3. Metal Saw Blade, AL08, Dry Cuts

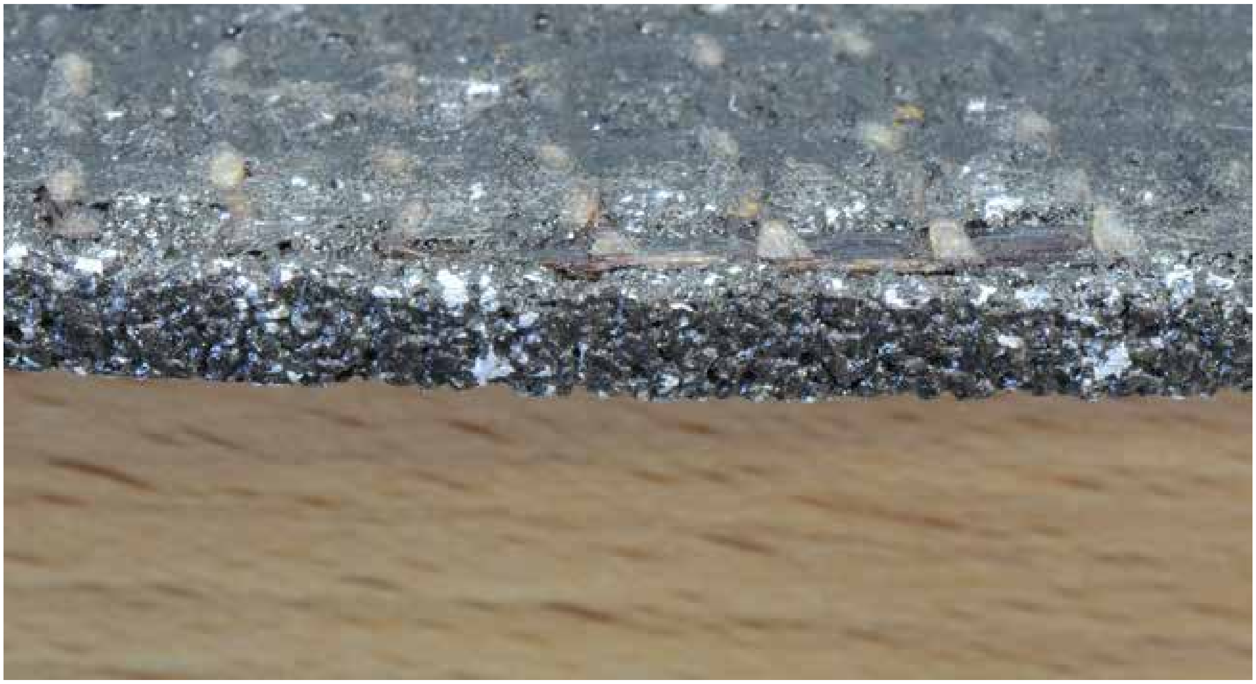


Figure C-4. Metal Saw Blade, AL08, Wet Cuts

Figure C-5. Metal Saw Blade, G3, Dry Cuts

Figure C-6. Metal Saw Blade, G3, Wet Cuts

Figure C-7. Metal Saw Blade, G5, Dry Cuts

Figure C-8. Metal Saw Blade, G5, Wet Cuts

Figure C-9. Metal Saw Blade, CF16, Dry Cuts

Figure C-10. Metal Saw Blade, CF16, Wet Cuts

Figure C-11. Metal Saw Blade, CF24, Dry Cuts

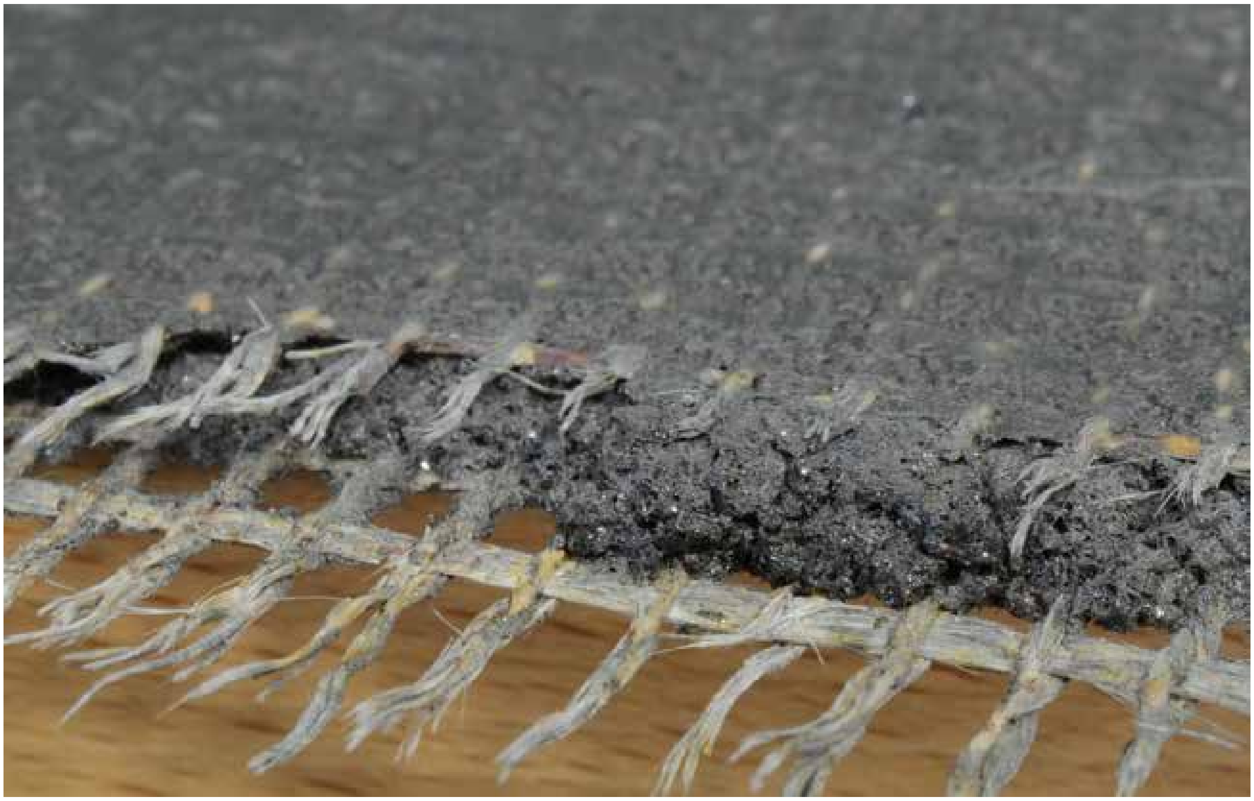


Figure C-12. Metal Saw Blade, CF24, Wet Cuts

Figure C-13. Concrete Saw Blade, AL06, Dry Cuts

Figure C-14. Concrete Saw Blade, AL06, Wet Cuts

Figure C-15. Concrete Saw Blade, AL08, Dry Cuts

Figure C-16. Concrete Saw Blade, AL08, Wet Cuts

Figure C-17. Concrete Saw Blade, G3, Dry Cuts

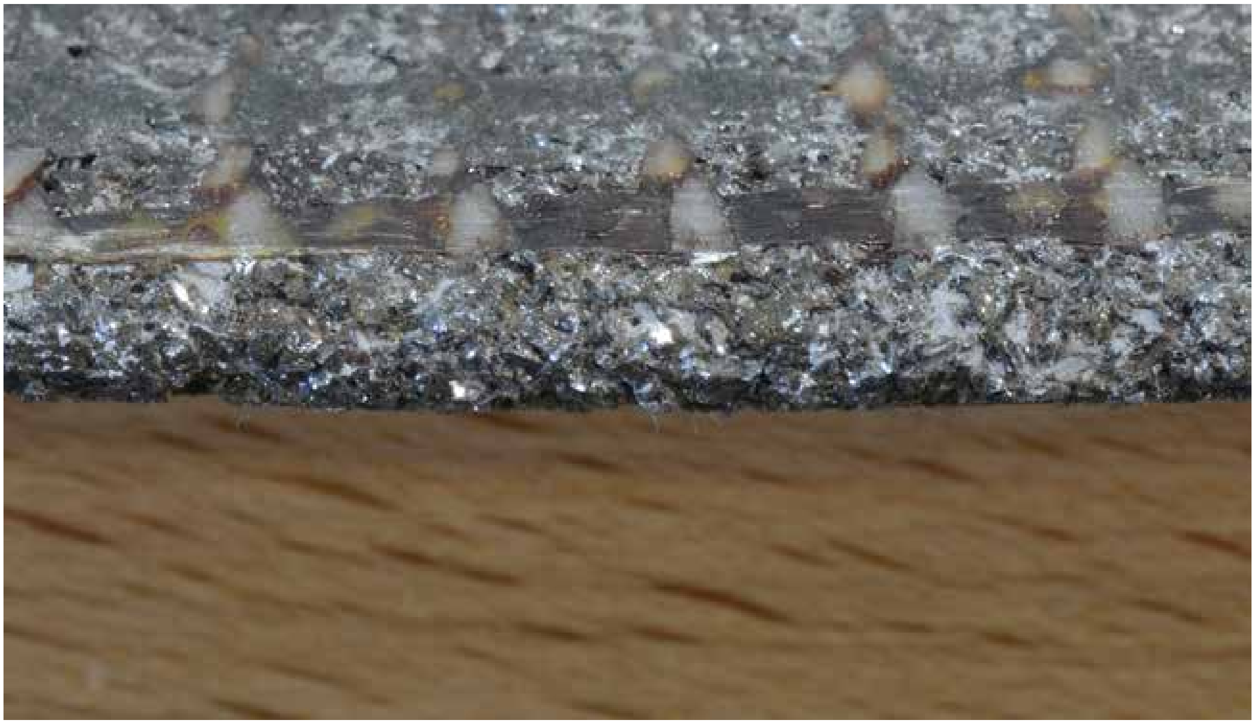


Figure C-18. Concrete Saw Blade, G3, Wet Cuts

Figure C-19. Concrete Saw Blade, G5, Dry Cuts

Figure C-20. Concrete Saw Blade, G5, Wet Cuts

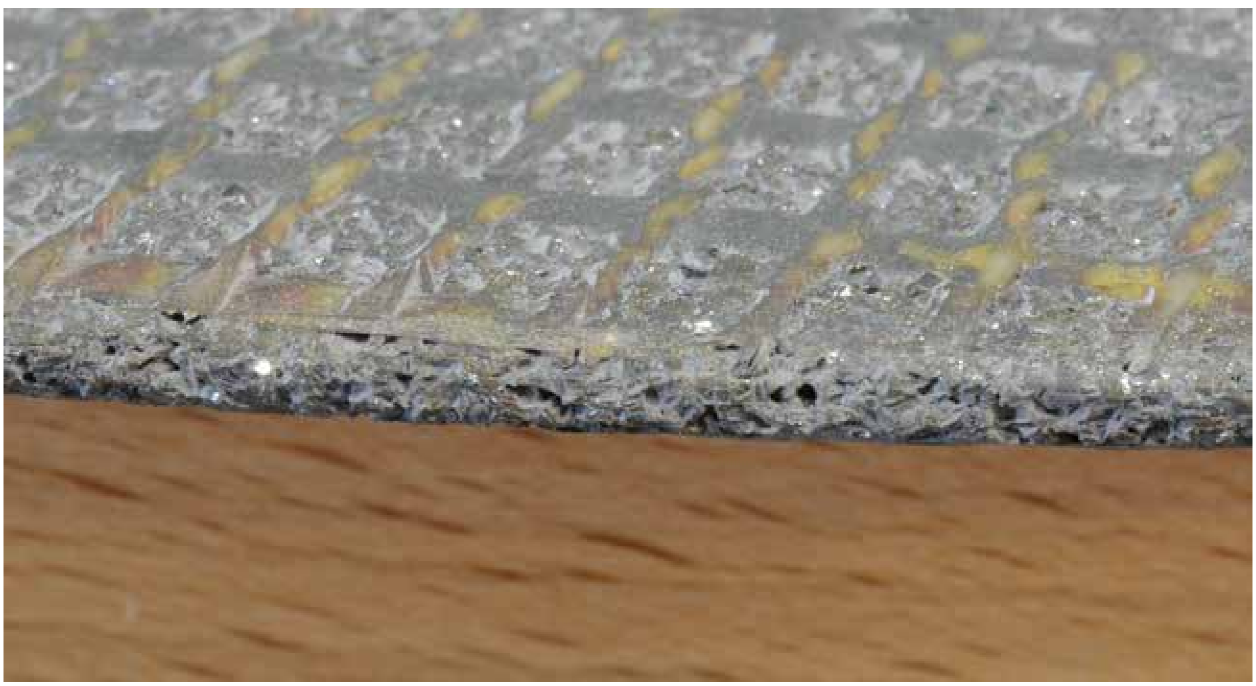


Figure C-21. Concrete Saw Blade, CF16, Dry Cuts

Figure C-22. Concrete Saw Blade, CF16, Wet Cuts

Figure C-23. Concrete Saw Blade, CF24, Dry Cuts

Figure C-24. Concrete Saw Blade, CF24, Wet Cuts

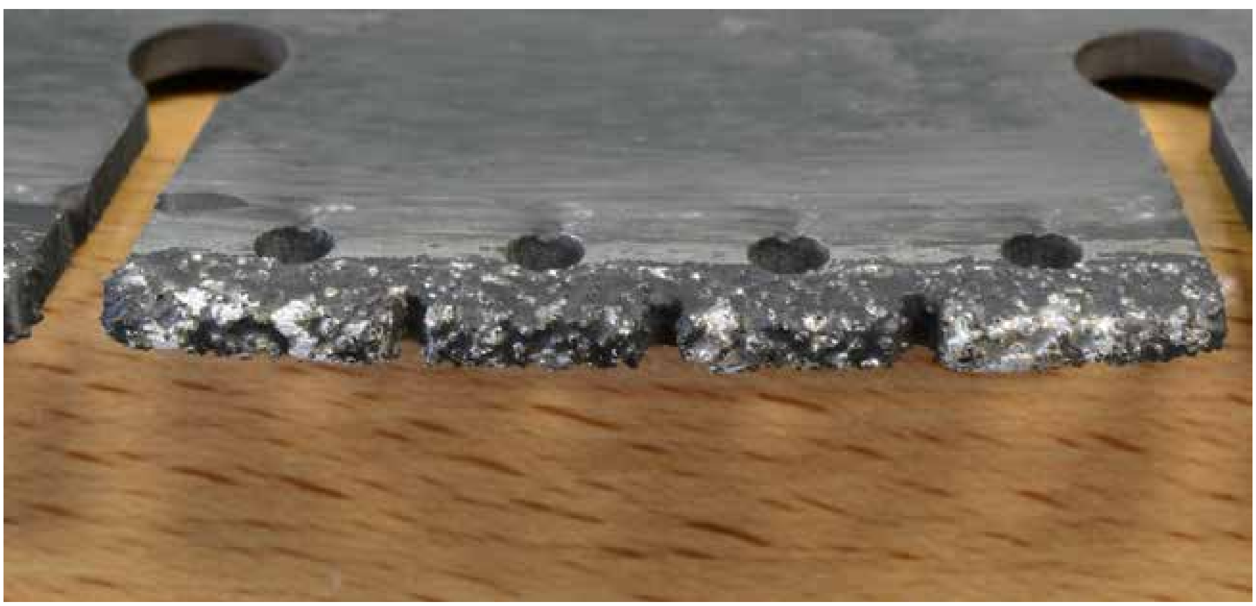


Figure C-25. Diamond Saw Blade, AL06, Dry Cuts

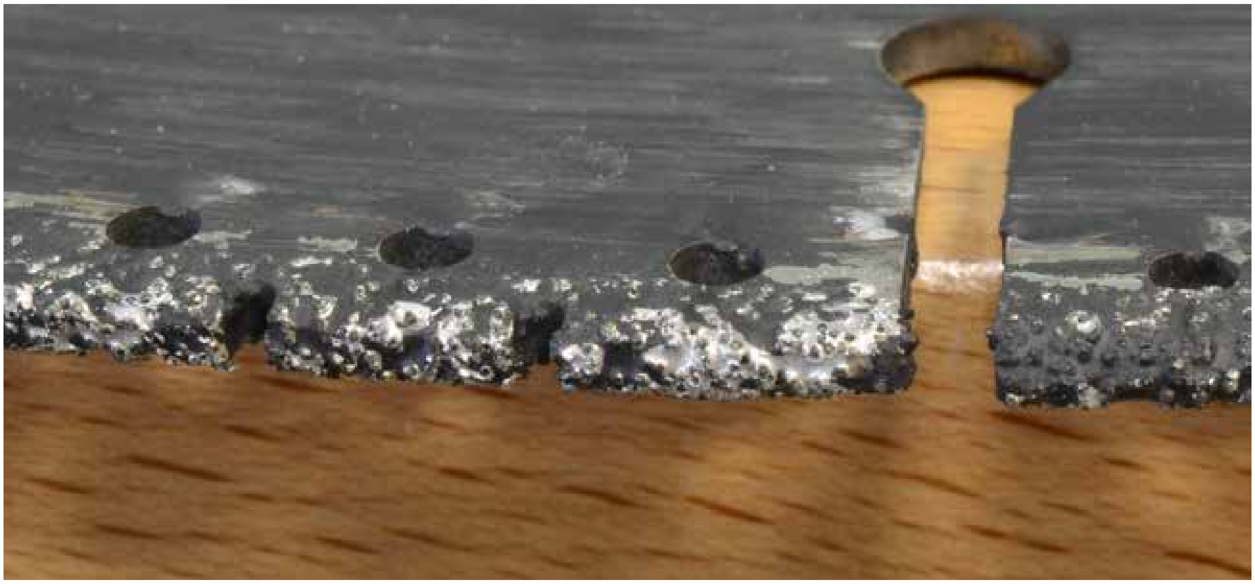


Figure C-26. Diamond Saw Blade, AL06, Wet Cuts

Figure C-27. Diamond Saw Blade, AL08, Dry Cuts

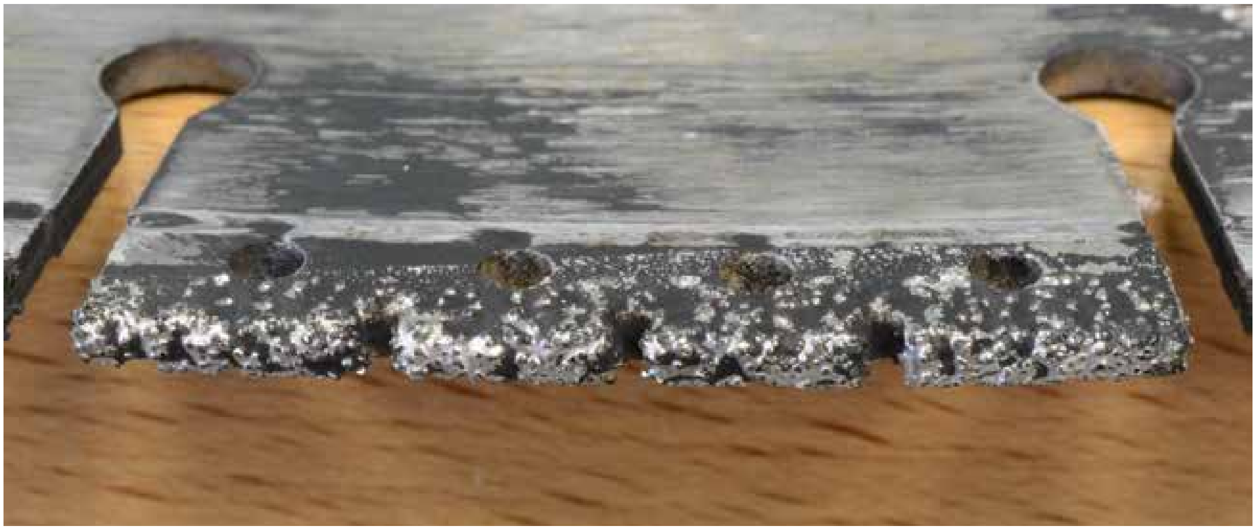


Figure C-28. Diamond Saw Blade, AL08, Wet Cuts

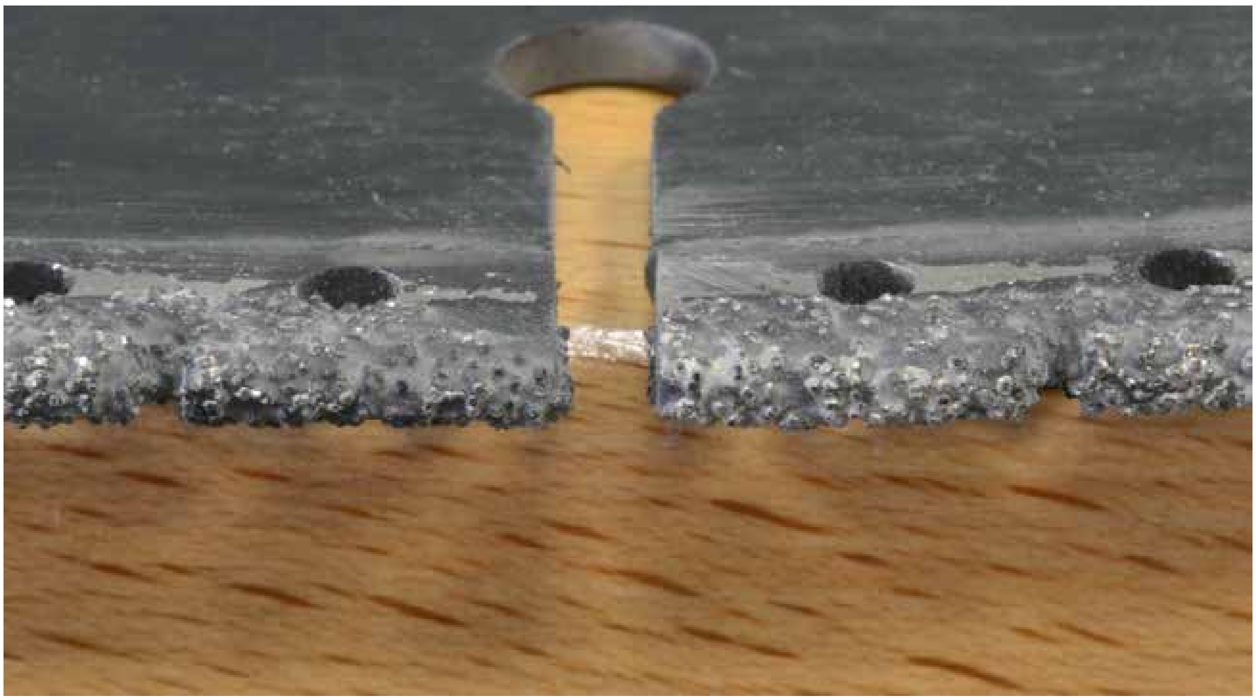


Figure C-29. Diamond Saw Blade, G3, Dry Cuts

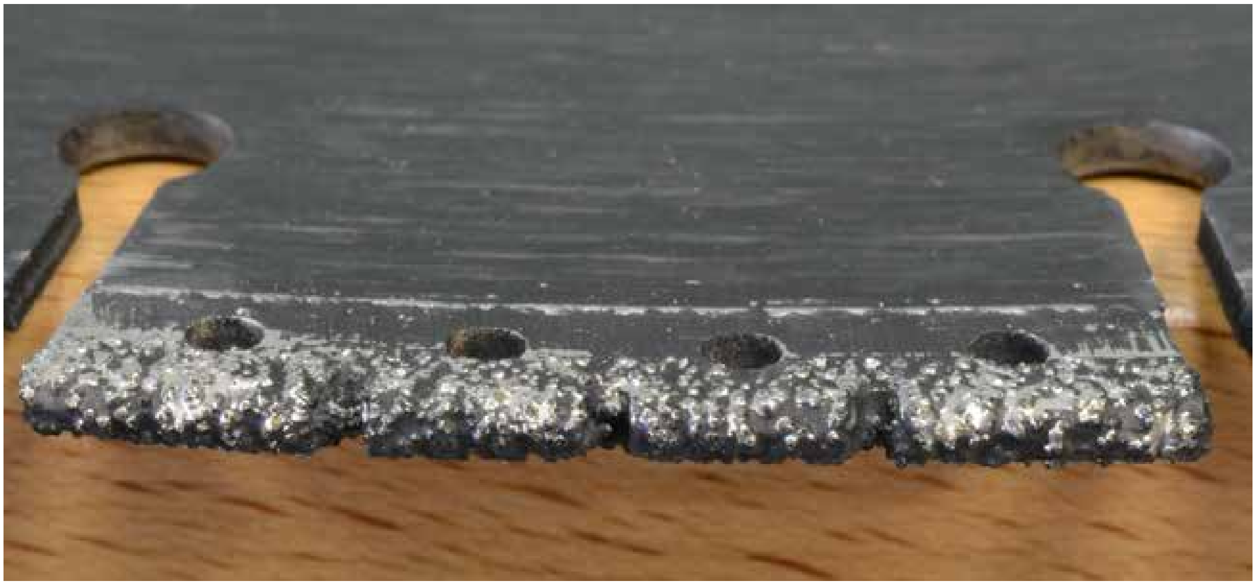


Figure C-30. Diamond Saw Blade, G3, Wet Cuts

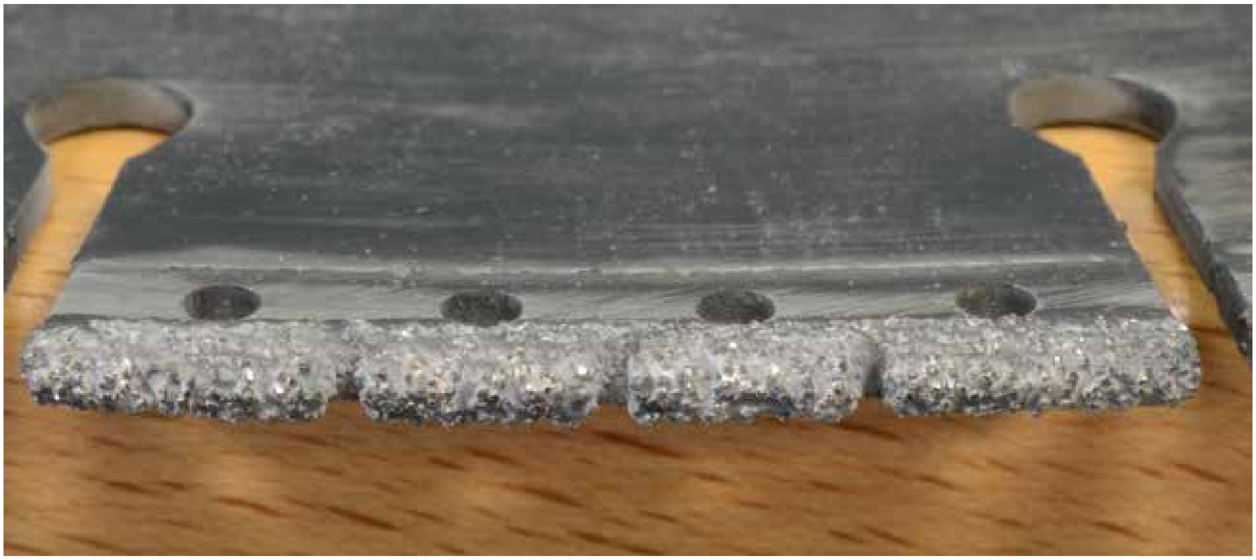


Figure C-31. Diamond Saw Blade, G5, Dry Cuts

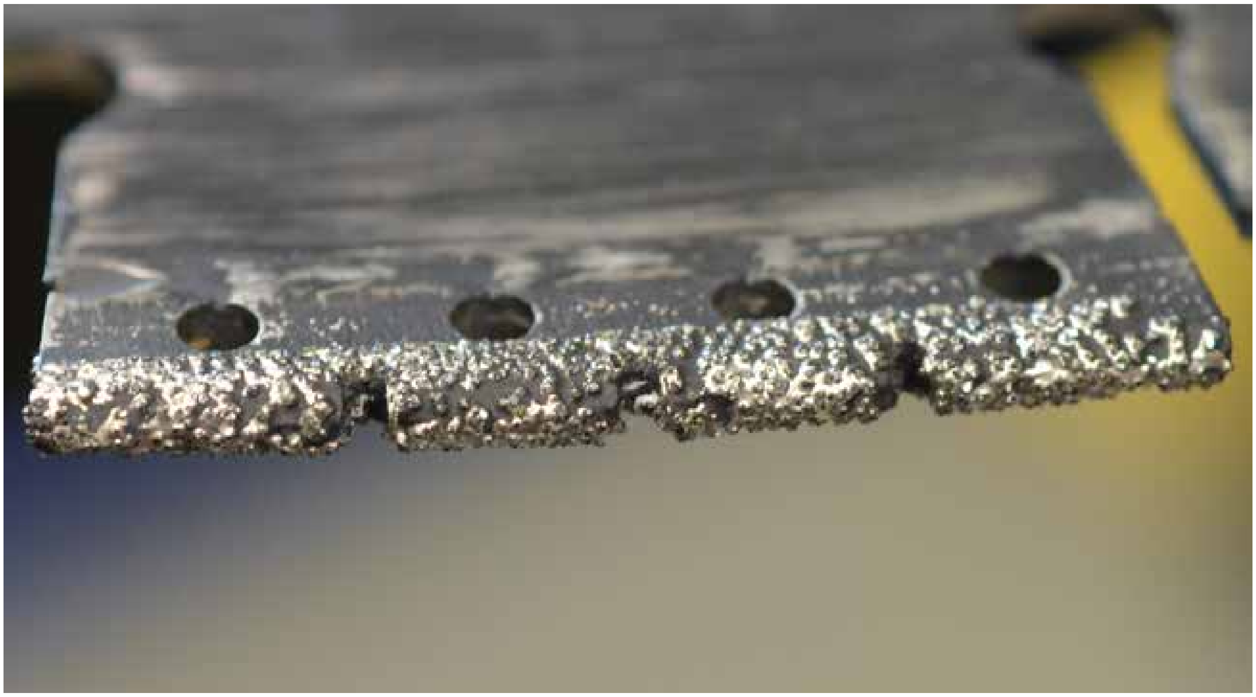


Figure C-32. Diamond Saw Blade, G5, Wet Cuts

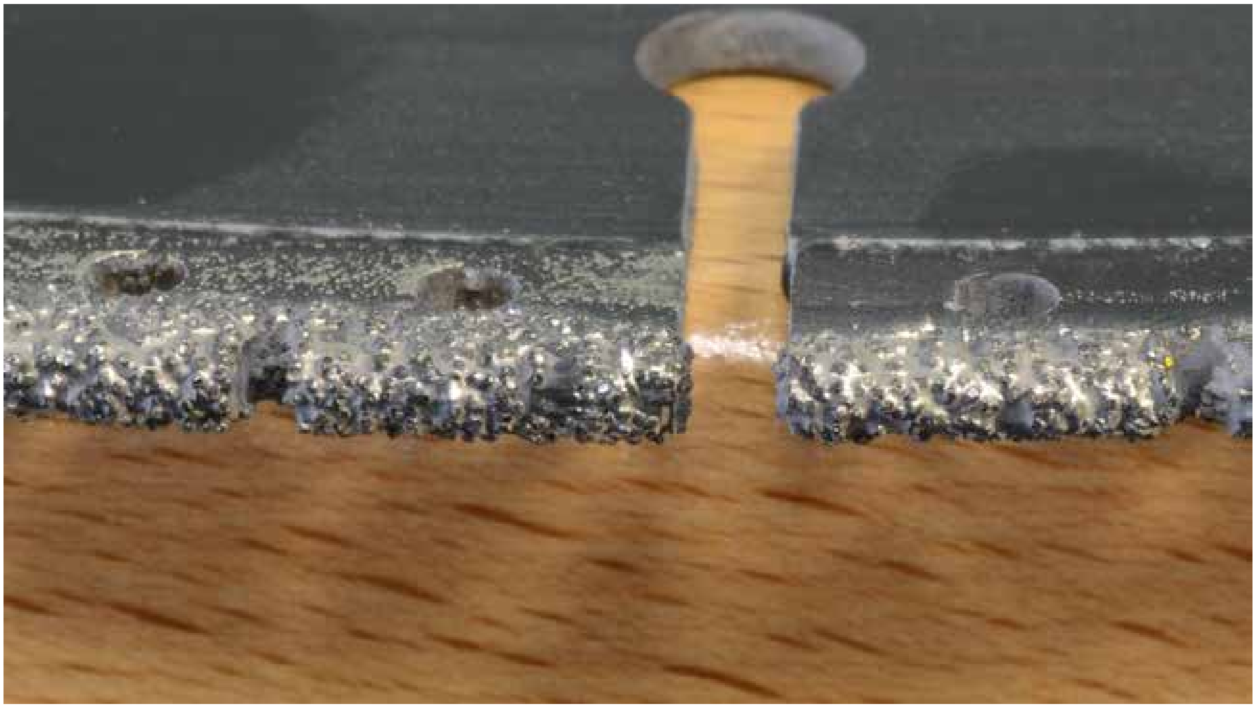


Figure C-33. Diamond Saw Blade, CF16, Dry Cuts

Figure C-34. Diamond Saw Blade, CF16, Wet Cuts

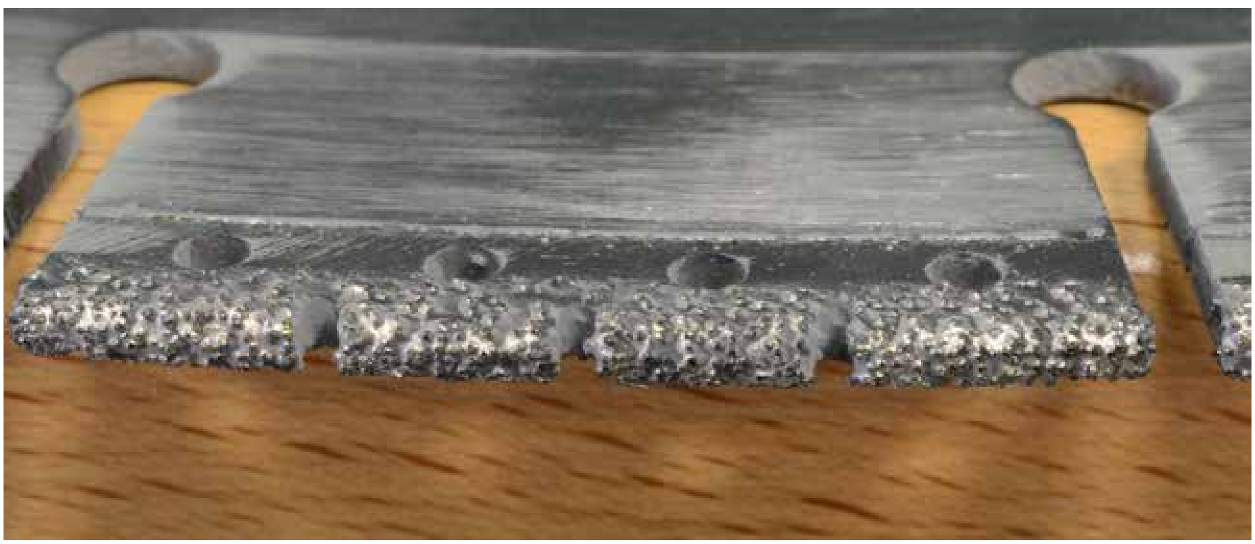


Figure C-35. Diamond Saw Blade, CF24, Dry Cuts

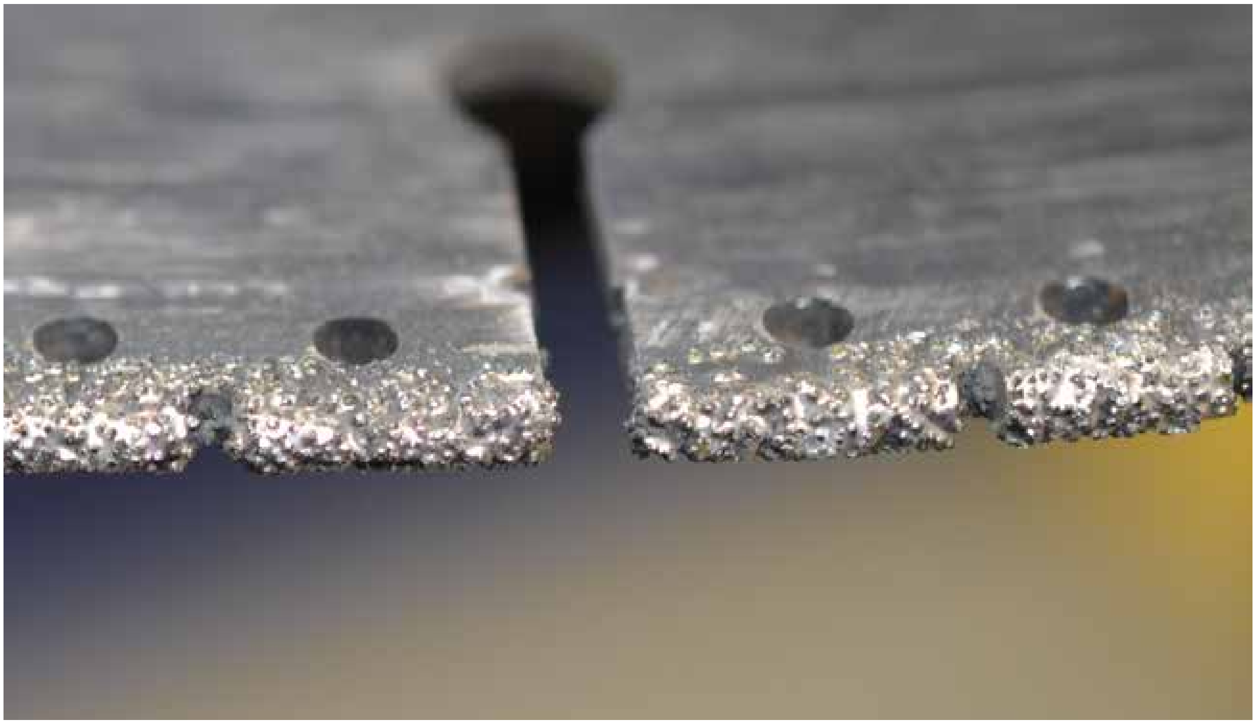


Figure C-36. Diamond Saw Blade, CF24, Wet Cuts

APPENDIX D—SAW BLADE WEAR MEASUREMENTS

Blade weight loss was calculated by taking the weight of each blade before and after each cut series. Blades used on the wet trial runs were air dried before being weighed after cutting. Table D-1 provides all blade weight comparisons. Cells highlighted in yellow indicate trial runs that did not have a full 24-cut series due to either the blade breaking or the cut rig binding up because of too much force being exerted.

Table D-1. Blade Wear Measurements

Test Series	Saw Blade Weight Loss (lb)	Saw Blade Diameter Loss (in.)	Pretest Weight (lb)	Posttest Weight (lb)	Pretest Diameter (in.)	Posttest Diameter (in.)
06 Metal Dry	10/100	25/100	2.855	2.76	15.9375	15.6875
06 Concrete Dry	21/100	47/100	2.275	2.065	15.9375	15.46875
06 Diamond Dry	0	0	5.01	5.01	16.125	16.125
06 Metal Wet	1/100	0	2.875	2.8625	15.9375	15.9375
06 Concrete Wet	7/100	22/100	2.2775	2.21	15.96875	15.75
06 Diamond Wet	0	0	4.965	4.965	16.125	16.125
08 Metal Dry	10/100	25/100	2.86	2.76	15.9375	15.6875
08 Concrete Dry	15/100	47/100	2.285	2.135	15.9375	15.46875
08 Diamond Dry	0	0	4.955	4.955	16.125	16.125
08 Metal Wet	-	-	2.875	-	15.9375	-
08 Concrete Wet	5/100	34/100	2.34	2.285	15.9375	15.59375
08 Diamond Wet	0	0	5.085	5.085	16.125	16.125
G3 Metal Dry	0	2/100	2.8575	2.8525	15.953125	15.9375
G3 Concrete Dry	4/100	9/100	2.3225	2.28	15.96875	15.875
G3 Diamond Dry	0	0	4.99	4.9875	16.125	16.125
G3 Metal Wet	-	-	2.845		15.953125	
G3 Concrete Wet	0	0	2.49	2.49	15.953125	15.953125
G3 Diamond Wet	0	0	4.965	4.9625	16.125	16.125
G5 Metal Dry	1/100	0	2.8675	2.855	15.9375	15.9375
G5 Concrete Dry	7/100	19/100	2.365	2.2925	16	15.8125
G5 Diamond Dry	0	0	4.9925	4.99	16.125	16.125
G5 Metal Wet	-	-	2.845	-	15.9375	-

Table D-1. Blade Wear Measurements (Continued)

Test Series	Saw Blade Weight Loss (lb)	Saw Blade Diameter Loss (in.)	Pre-Test Weight (lb)	Post Test Weight (lb)	Pre-Test Diameter (in.)	Post-Test Diameter (in.)
G5 Concrete Wet	0	0	2.285	2.285	15.9375	15.9375
G5 Diamond Wet	0	0	4.955	4.955	16.125	16.125
CF16 Metal Dry	0	0	2.905	2.9025	15.9375	15.9375
CF16 Concrete Dry	5/100	11/100	2.365	2.3125	15.953125	15.84375
CF16 Diamond Dry	0	0	5	4.995	16.125	16.125
CF16 Metal Wet	0	0	2.85	2.85	15.953125	15.953125
CF16 Concrete Wet	0	0	2.2425	2.2425	15.953125	15.953125
CF16 Diamond Wet	0	0	5.015	5.0125	16.125	16.125
CF24 Metal Dry	1/100	0	2.9025	2.8925	15.953125	15.953125
CF24 Concrete Dry	2/100	0	2.3075	2.285	15.953125	15.953125
CF24 Diamond Dry	0	0	5.0925	5.0875	16.125	16.125
CF24 Metal Wet	-	-	2.845		15.9375	
CF24 Concrete Wet	1/100	0	2.375	2.365	15.9375	15.9375
CF24 Diamond Wet	0	0	4.97	4.97	16.125	16.125

APPENDIX E—PARTICULATE ANALYSIS

E.1 ANALYSIS.

Respiratory hazards were assessed during saw blade type evaluations in this research effort. During four days of saw blade type testing, the William J Hughes Technical Center Safety Office collected integrated air samples during all test runs for analysis using the following methods:

- Respirable particulates, National Institute for Occupational Safety and Health (NIOSH) 0600
- Elemental carbon, NIOSH 5040
- Glass fiber, NIOSH 7400B
- Carbon fiber, NIOSH 7402 modified for carbon fiber

Figures E-1 through E-5 [E-1] show the results of that analysis.

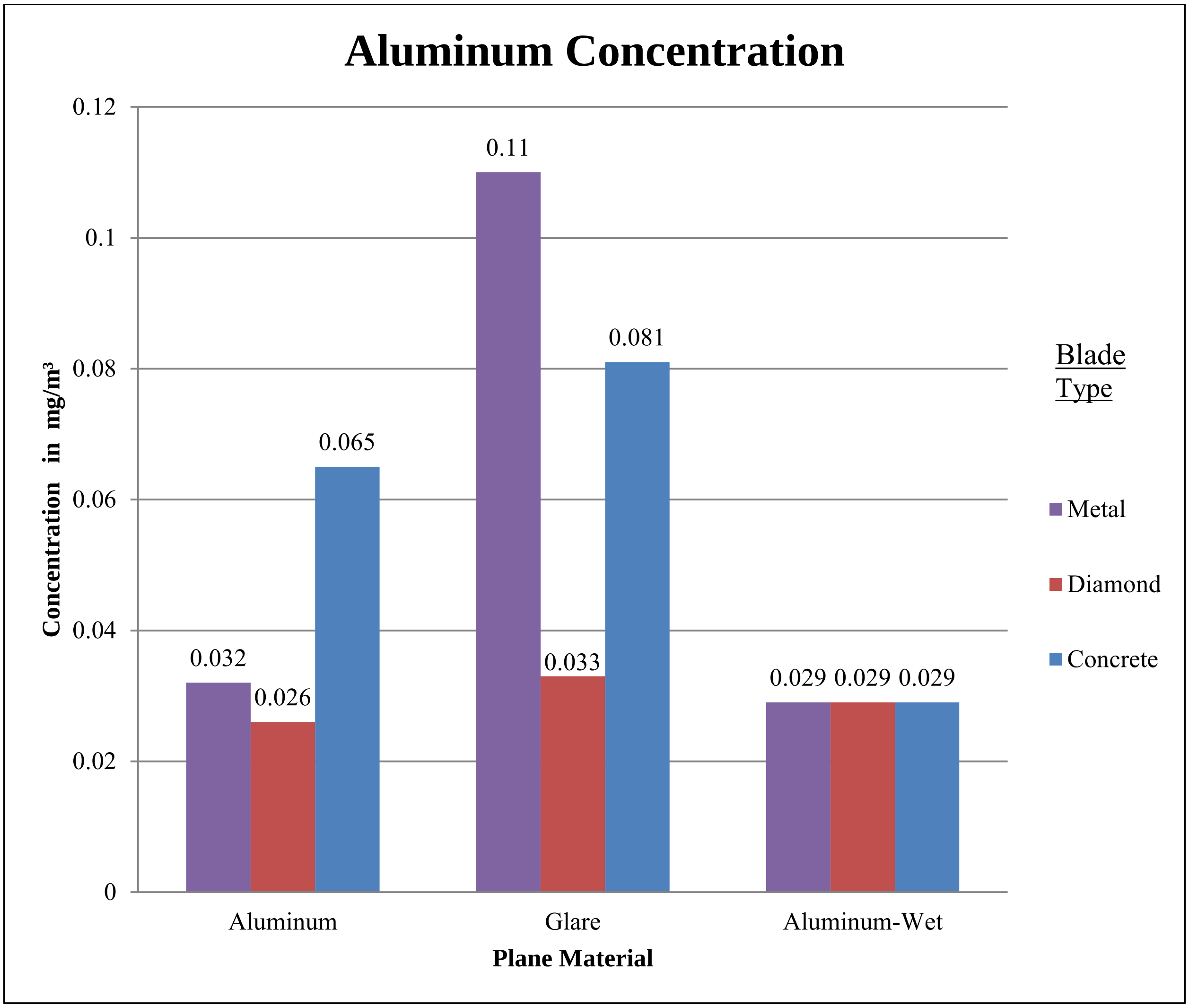


Figure E-1. Aluminum Particulates Concentration [E-1]

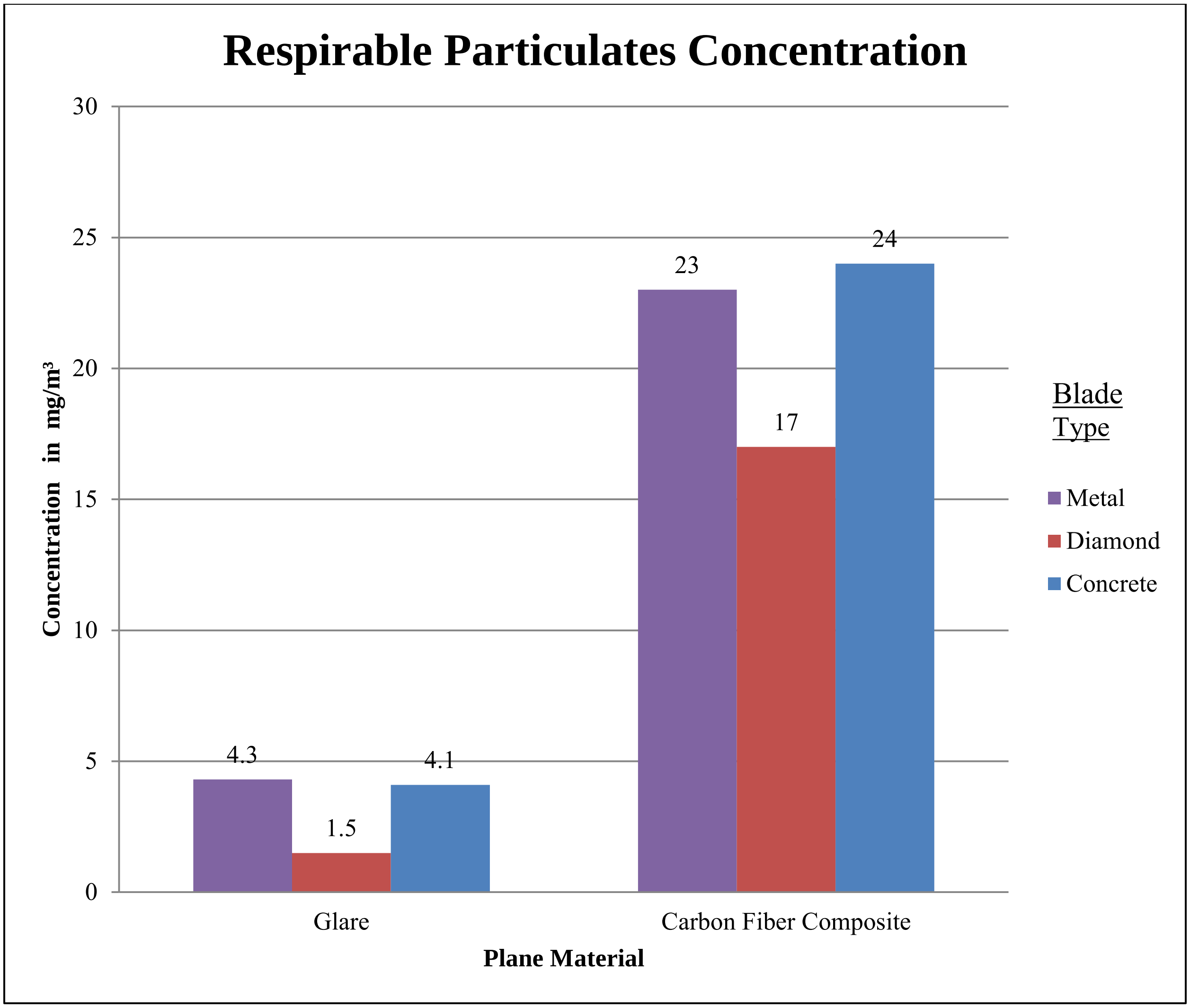


Figure E-2. Respirable Particulates Concentration [E-1]

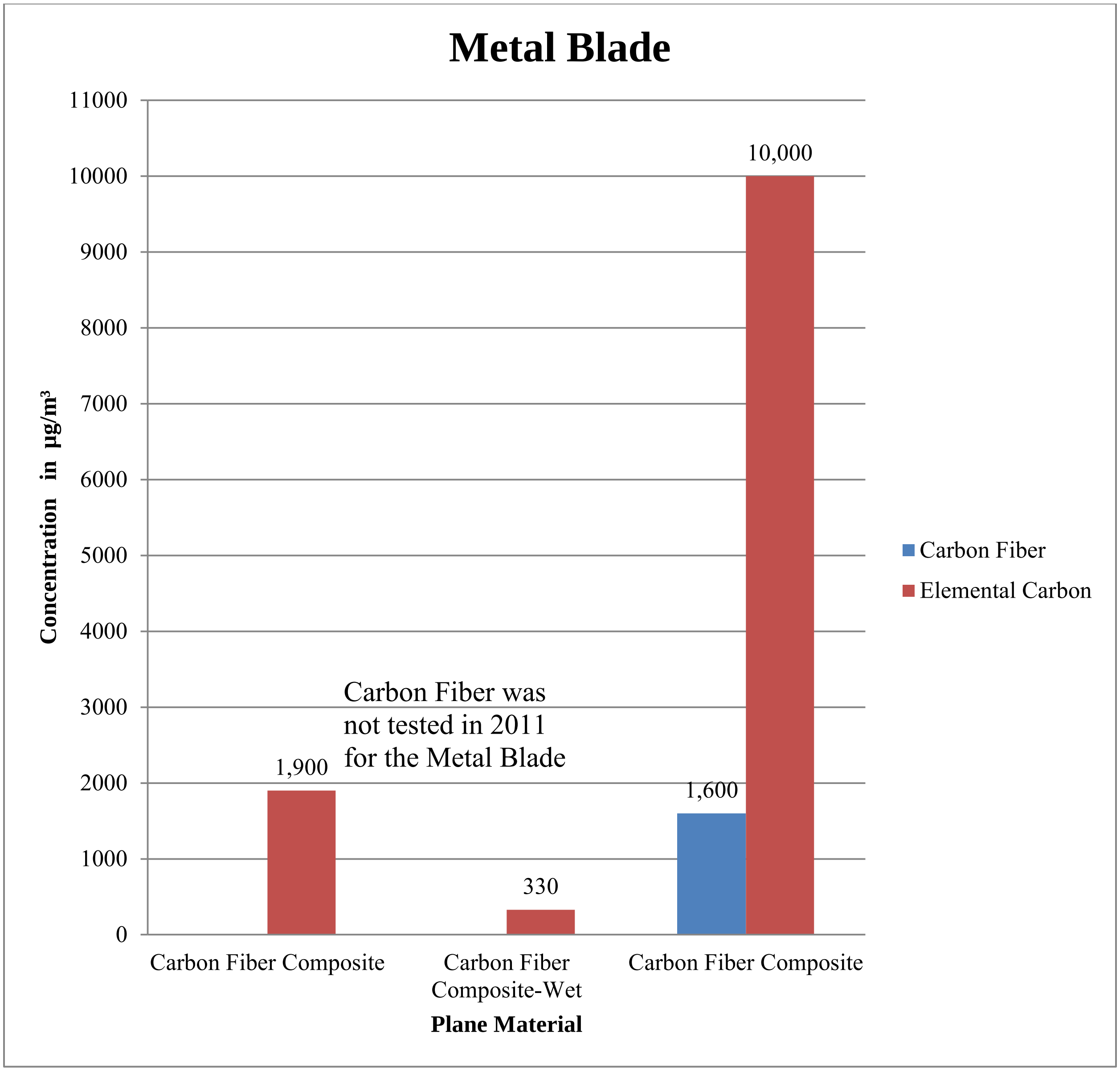


Figure E-3. Carbon Particulate Concentration for Metal Saw Blade [E-1]

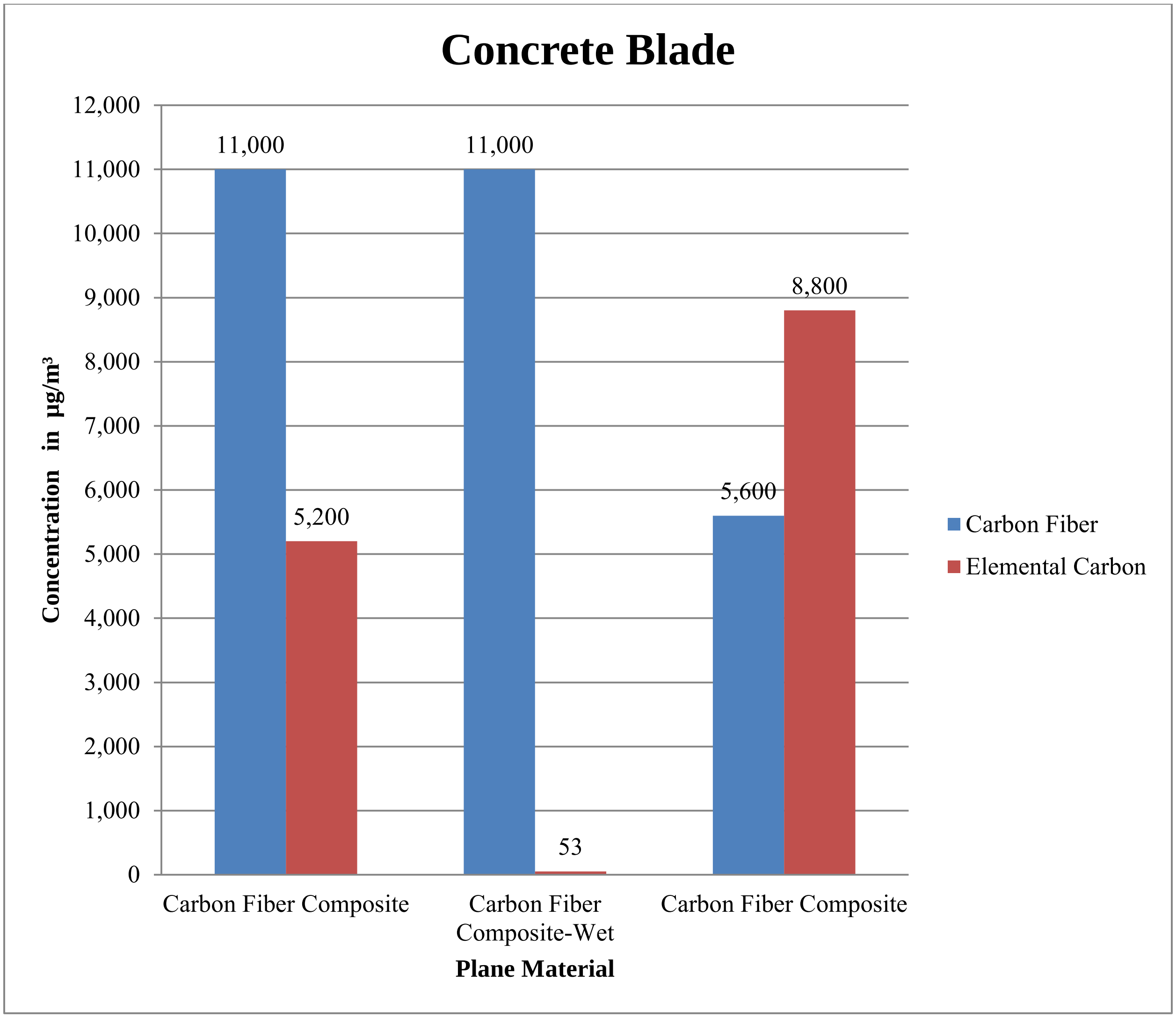


Figure E-4. Carbon Particulate Concentration for Concrete Saw Blade [E-1]

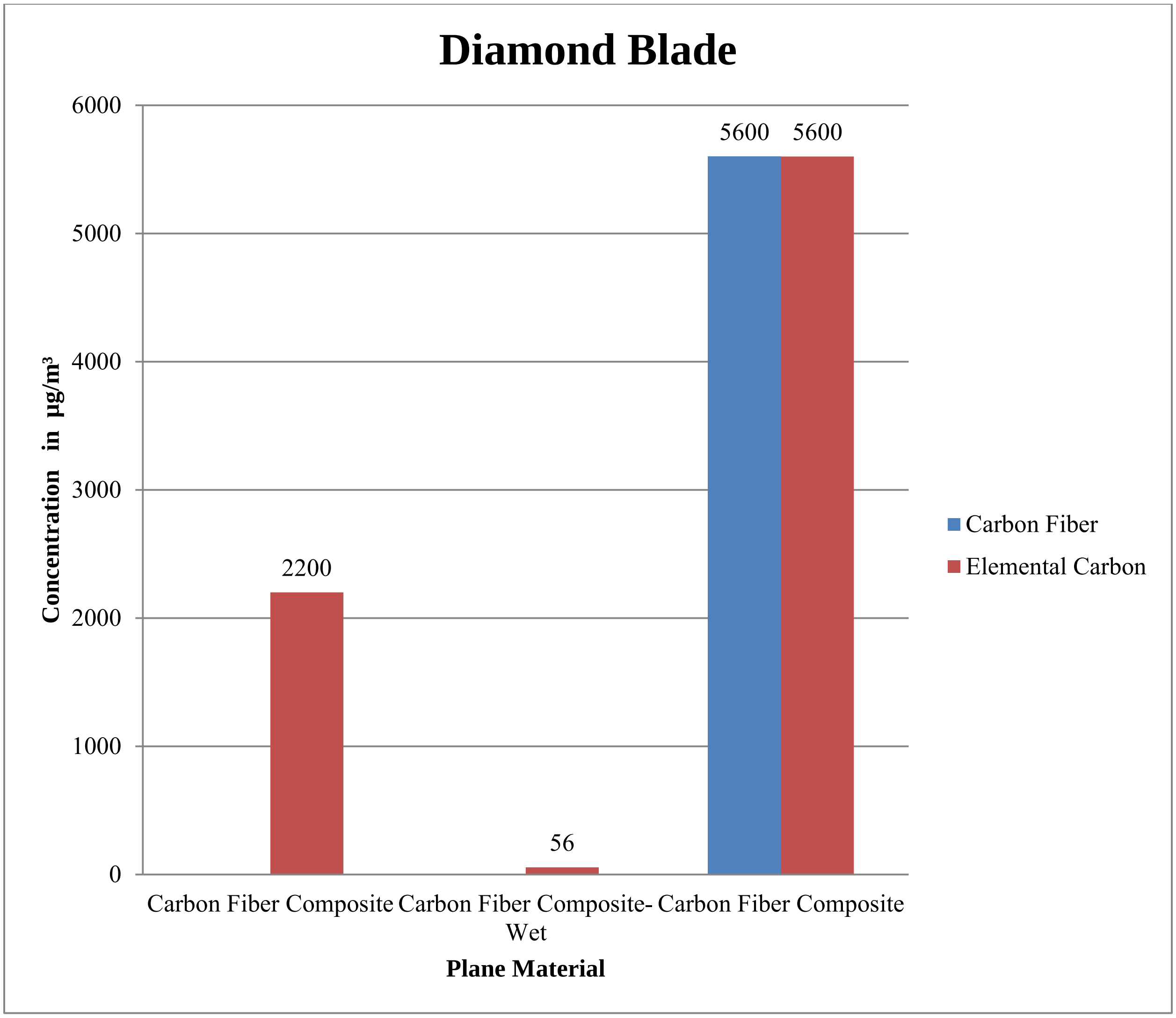


Figure E-5. Carbon Particulate Concentration for Diamond-Tipped Saw Blade [E-1]

E.2 REFERENCE.

E-1. Shara, J., "FW: Test Results," email to the author of this report, January 16, 2015.