The respirable effects of a spark generated plasma on carbon fibre

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Abstract

It was recently discovered, that when simultaneously burned and broken, carbon fibre reinforced plastic releases small sharp fibres that act as a respiratory irritant. These sharp fibres have physical properties highly reminiscent of asbestos. It was suggested that electrical abuse could produce similar results.

The objective of this experiment was to determine whether potentially dangerous levels of airborne fibres are released when carbon fibres are exposed to an electric plasma, as may occur naturally if carbon fibre composite is struck by lightning. An arc welder was used to produce an electric plasma, an air sampler was used to collect samples for analysis and a scanning electron Microscope (SEM) was used to provide images of the samples that were created during the course of this investigation.

The analysis showed that under simulated conditions, up to 955 times the safe airborne concentration for the more dangerous forms of asbestos were released. Asbestos was used as a comparison with respirable/inspirable carbon fibres due to their similar properties. The carbon fibres showed all characteristics of being a chronic health risk and were found in potentially hazardous quantities. Further research is suggested to determine the applicability of this hazard to real life situations.

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Aim

To discover whether carbon fibre can release dangerous airborne inspirable and/or respirable fibres when abused in a spark generated plasma.

1. Introduction

1.1 Background

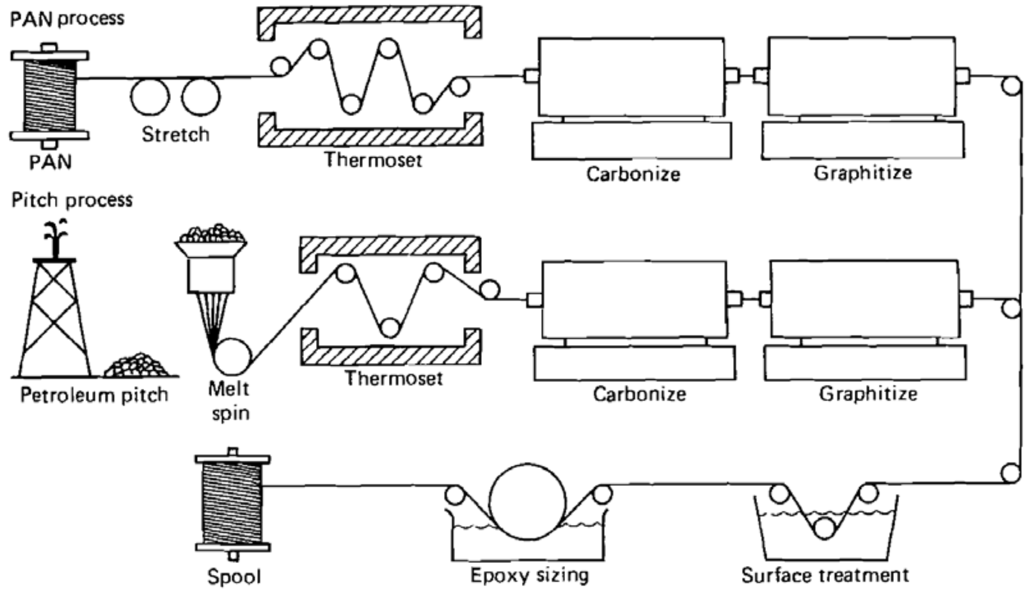
The construction of upper price items of all kinds has been revolutionised by incredibly strong and light composites, generally ones including carbon-based products. The current material that has taken the world by force is carbon fibre. Although carbon fibre has existed for well over a decade, only recently has it been commonly available at a reasonable price due to industrial advances. Carbon fibre is now present in almost everything considered high performance including sports equipment, bicycles, and expensively branded cars. Increasingly, large quantities can also be found in aircraft (Carbon Fibre Hood, 2009). However, as this astonishingly tough material becomes more widespread; safety-wise there are still some risks that have only recently begun to be appreciated and understood, such as the release of small, sharp and rigid particles when it is abused in various ways (Andrews, p. 1, 2008).

1.2 Production of carbon fibre

Carbon fibre can be created in various ways, at various temperatures and pressures depending on the desired properties of the carbon fibre. The most common form, which will be discussed in this report, is epoxy reinforced carbon fibre. The manufacturing methods for carbon fibre reinforced epoxy, which is the strong, solid black material we see today everywhere, can be varied. The first variable is the orientation and length of the individual carbon fibres: they can be long and parallel, they can be short and mismatched in every direction, they can even be woven into rugs (Dragon Plate, 2010). There are many other ways in which the fibre can be placed to give the finished product different properties, like being very strong in one direction but weak in the other, or not as strong in any single direction, but instead equally strong and inflexible in every direction, or being strong but brittle (Dragon Plate, 2010). The way in which carbon fibres are set in the epoxy substrate also affects the properties of the finished material.

Carbon fibre products can be manufactured using the traditional composite fibre methods of putting the fibres in a mould as a random layer of chopped strands, filling the mould with epoxy, then essentially kneading out the air bubbles. However, this method causes inconsistencies in the final product, resulting in approximately 20%-30% reduction in most performance categories (flexibility, strength, hardness) as compared to carbon fibre products that have been professionally manufactured using more sophisticated methods for laying up the fibres and applying the epoxy (NSX Prime, 2000). The actual production of the fibres varies greatly with heat treatments and stretching, but the larger difference is made by the actual process used for carbon fibre manufacture. The polyacrylonitrile (PAN) process is now more common, and the pitch process uses petroleum pitch.

Figure 1. Production of Carbon Fibre



(Walsh, P. 35, 2001)

The PAN process uses pre-manufactured PAN (polyacrylonitrile) fibres which are then processed to form carbon fibres cheaply and economically. All of the processes that can be seen in figure 1 with the exception of carbonisation, epoxy sizing and graphitisation are designed to orient and crosslink the molecules to provide a high tensile strength (Walsh, 2001).

In the Pitch process, pitch is created from a fossil fuel or fossil fuel product. It is then refined to “... obtain the desired viscosity and molecular weight, in preparation for making high-performance carbon fibers”. The pre-processed pitch contains "mesophase", a term for a disk-like liquid crystal phase that develops regions of long-term ordered molecules favourable to manufacture of high-performance fibers” (Walsh, P.36, 2001). This essentially means that the refined pitch is an expensive material to produce but is ideal for making carbon fibre; thus, it already possesses the properties that PAN is processed to create, so when it receives some of the manufacturing treatments, these properties are magnified even further. The carbon fibre produced using the Pitch process is more expensive and higher quality in almost every way compared with the PAN process (Walsh, 2001).

The best strength to weight ratio is provided by the fibres when they are not set in epoxy, however in this form they are relatively dense with a density 1.75 times that of water. The ultimate breaking tensile strength of carbon fibre is 5650 Megapascals (MpA) as compared to tungsten at 1,510, titanium at 900, stainless steel at 860, human hair at 380, cast iron at 220, bone at 130 and concrete at an impressive 3. It is only surpassed by carbon

nanotubes which can have a strength as high as 63,000 MpA (Pavlina, et al, 2008), (Pilling, 2009).
When carbon fibre is set in epoxy, “... There are two ways to create a fiber reinforced laminate; "wet" layup and pre-impregnated fiber layup.” (NSX Prime, 2000). The wet method is the method where the carbon fibre is simply used in a mould with a method of removing air bubbles, however the pre-impregnated method is far more modern, consistent and diverse. As the name may suggest, the carbon fibre is “pre-impregnated” in a factory with epoxy before it is ever made into a usable, solid, shaped object. From there, there are different ways to create the final product: “The first method of curing a pre-impregnated laminate is to put it under vacuum bag compaction and place it in an oven for the prescribed amount of time until the resin "glasses", flows and hardens in the shape of the parent mould.” (NSX Prime, 2000), “The second method employs the same vacuum bag compaction as the first, but adds the extra force of the autoclave to "pressure cook" the laminate. In both instances, the cure temperature will also be the maximum allowable temperature of the cured laminate, with a continuous service temperature slightly lower. This temperature generally resides between 250 and 350 degrees Fahrenheit” (NSX Prime, 2000).
Many method variations have been applied to these two methods but they are generally for specific shapes, like very thin curves or perfectly flat sheets. These methods are the staples of how carbon fibre is made.

1.3 Preliminary Examination

Figure 2: Carbon fibres

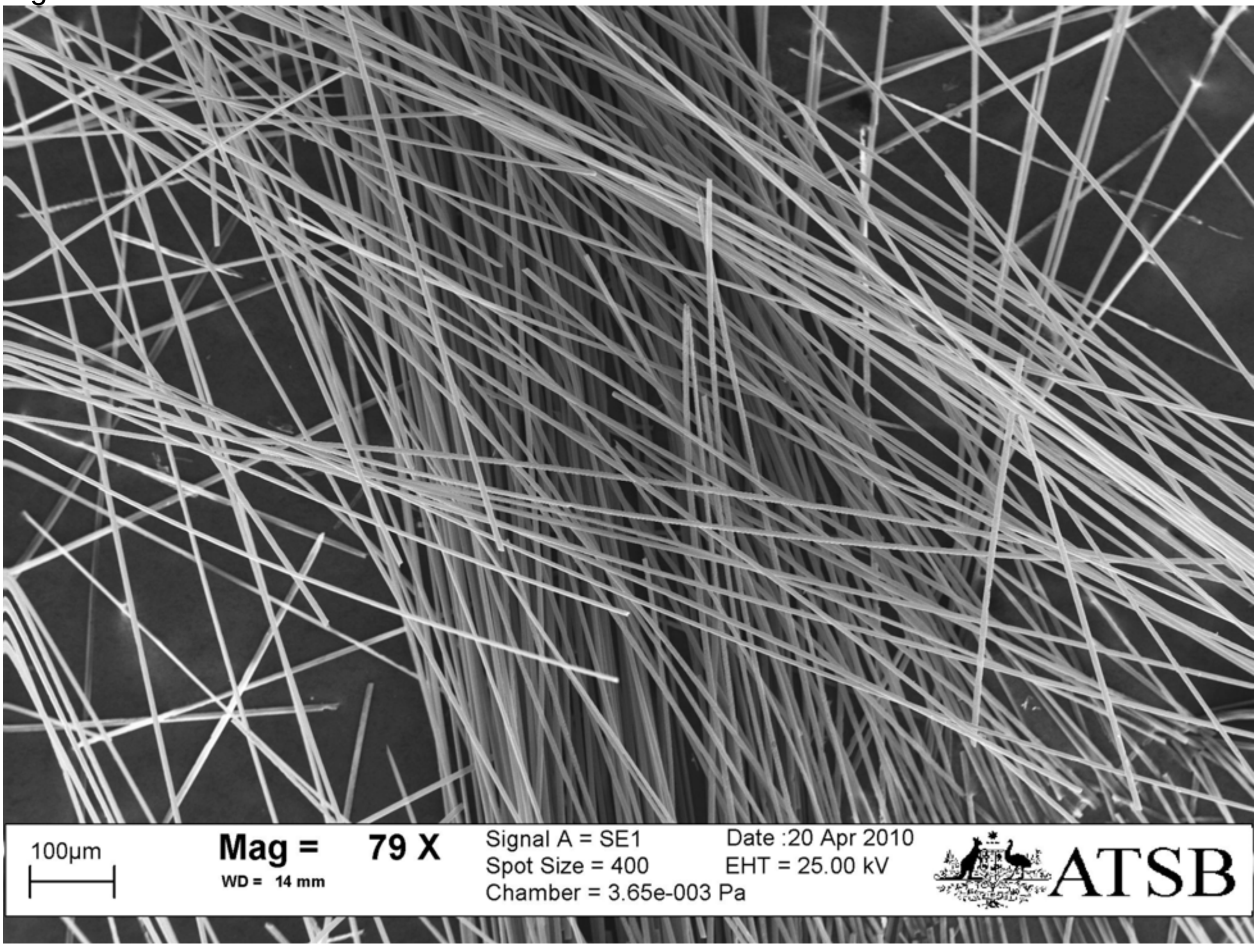


Figure 2 shows a bunch of fibres released by the experiment, viewed with a scanning electron microscope (SEM), the 100 micron scale shown is the same width as a Caucasian human hair, which provides a reference point for how thin the fibres can be.

Figure 3: The end of a mechanically cut carbon fibre

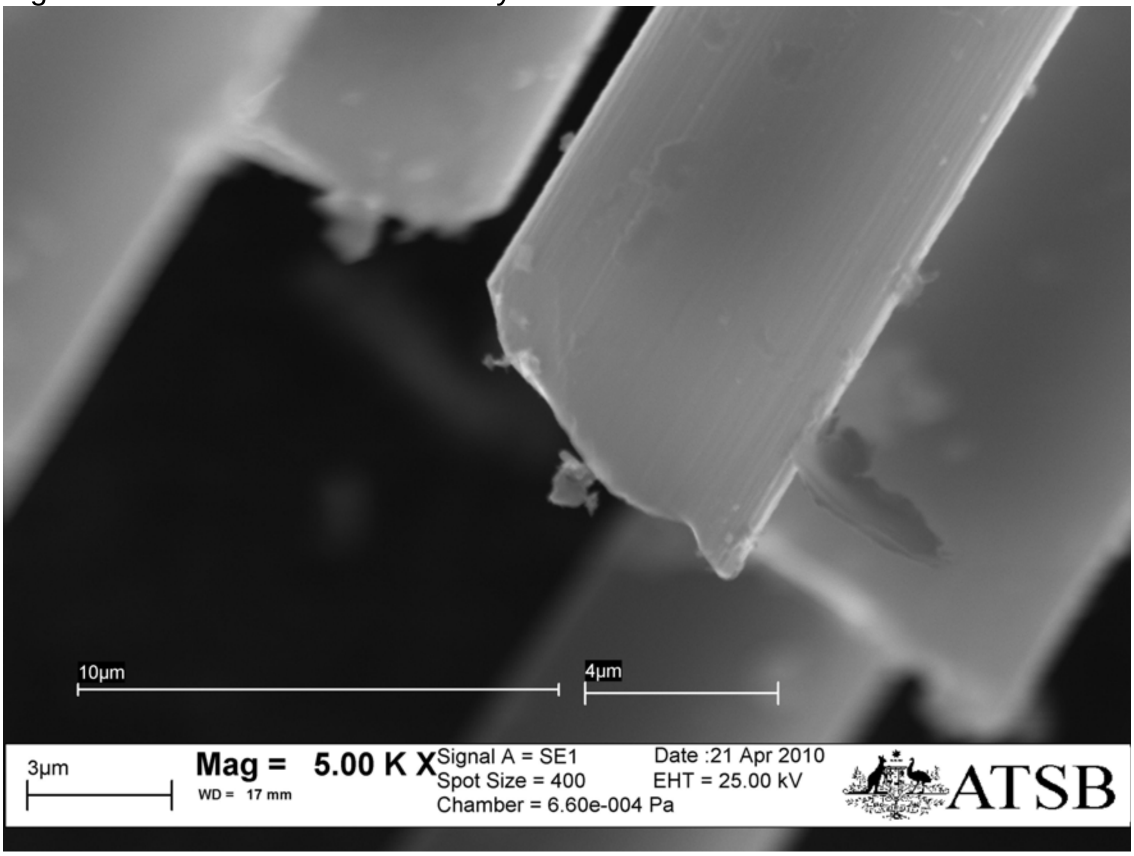
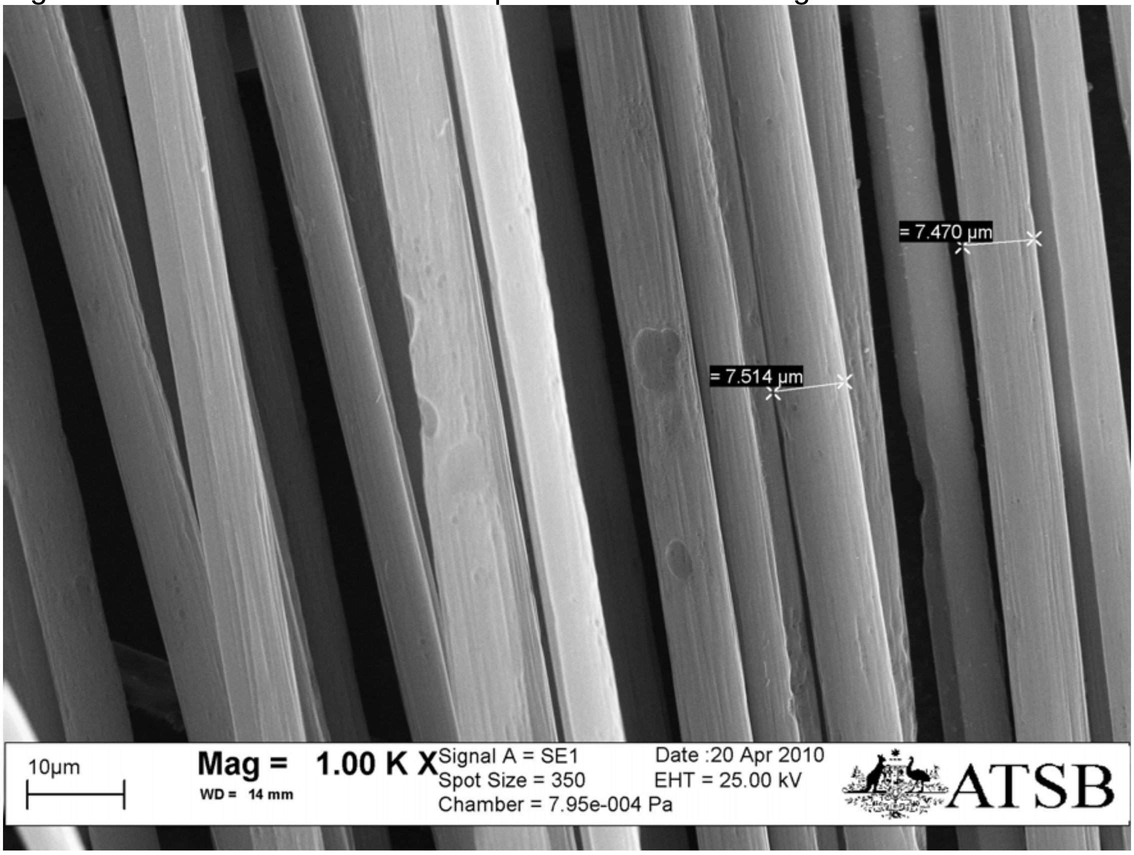


Figure 3 shows a control fibre at 5,000X where fibres had only been exposed to electric current long enough to burn away the epoxy, (from the preliminary testing). This image shows the consistency of carbon fibres, the uniform cut in between perpendicular and 45 degrees which is how carbon fibre usually splits under normal circumstances (in this case scissors). Also the faint grooves created during the manufacture process can be seen, where the carbon fibre has been pulled through a mandrel to create uniform fibres.

It can be seen that apparently the preferred initial route for the electricity is down those grooves, and seemingly the concentration of electricity erodes the carbon fibre around the grooves leaving fewer, wider, deeper grooves in the fibres.

A preliminary examination was performed of the fibres that were liberated from the epoxy, to assess the effect that the electric current had had on the carbon fibres themselves, and some very interesting results were returned.

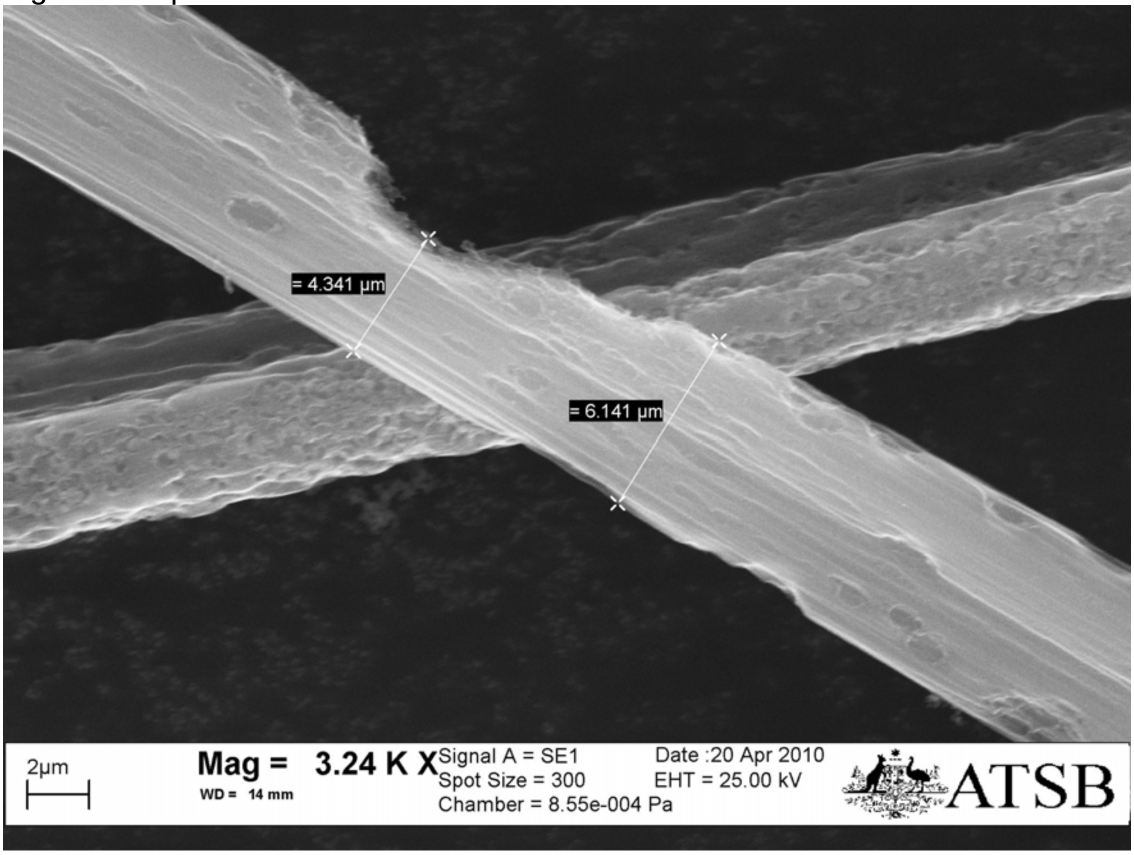
Figure 4: Carbon fibres with minor plasma related damage



Normally carbon fibres have a consistent cross section, whether or not they are broken. However, as can be seen in figure 4, the fibres now have different cross sections, with eroded dimpled areas. Another visible effect is that many fibres have erosions like long scratches down the sides and the fibres appear less round. This effect is interesting, but not relevant to this report. However, in this picture, although the fibres are imperfect and inconsistent, they are obviously still intact, of similar sizes and do not appear to be structurally compromised.

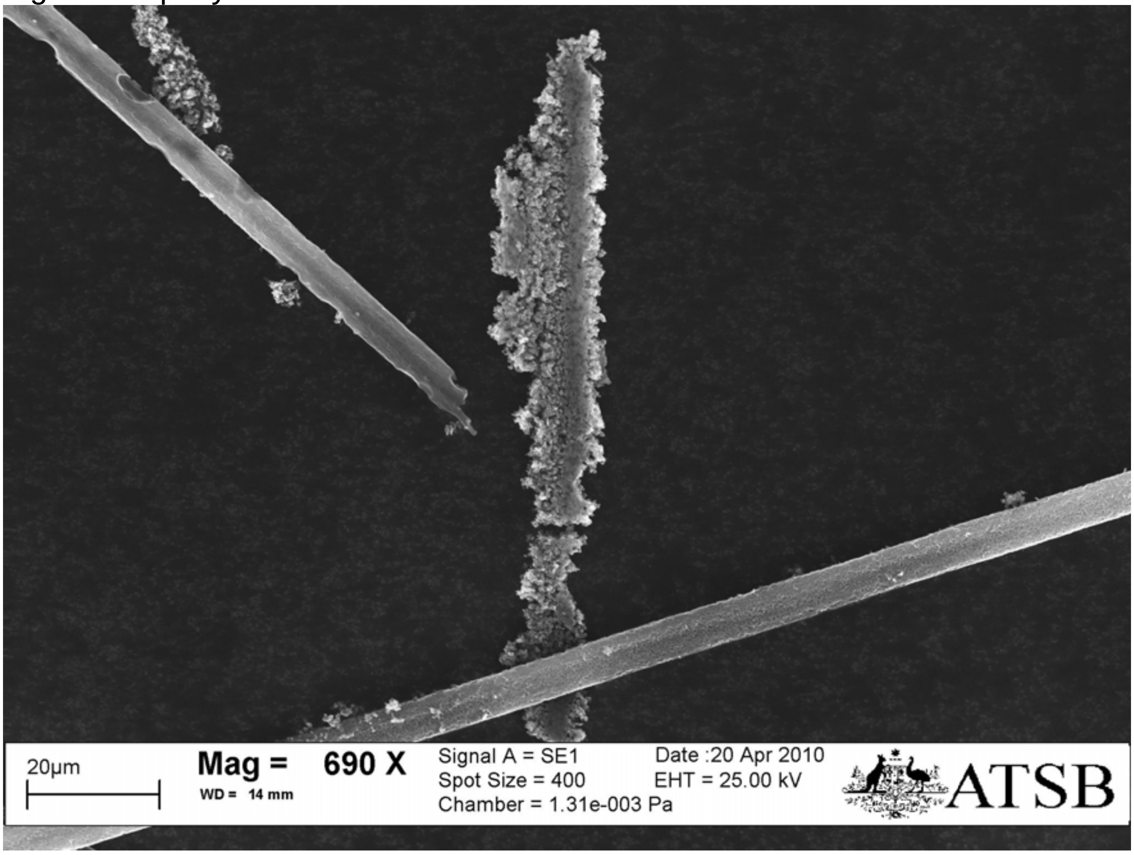
However, if you look at the fibres that had been in the areas that had been exposed to a plasma arc, the loose fibres provided far more interesting images.

Figure 5: Square Erosion



In Figure 5 both fibres have eroded into square cross sections, suggesting that the PAN process of manufacture that was used for these particular fibres makes them more vulnerable to eroding to a square cross section. Also, both fibres have a smaller cross section than the uniform fibres in figure 3. The lower fibre's surface is ragged and uneven mainly due to its surface being pitted with hundreds of holes less than 0.5 microns wide. The fibre in the foreground is even more interesting as there is an eroded chunk that has structurally compromised the fibre, with small "feathers" of carbon fibre in the crater. This small scale examination provided more questions on the cratering process on the fibres when they are exposed to a plasma arc, as this is the clearest phenomenon that was observed during the preliminary tests.

Figure 6: Epoxy bound carbon fibre



In figure 6 there is a uniform fibre across the bottom with only small pits, and a fibre in the top left with multiple craters. The fibre in the centre is a fairly small loose fibre that could easily become airborne, however this fibre is still coated with epoxy resin. The National occupational health and safety commission (NOHSC) asbestos counting method (2005) states that fibres that are encased in this way should not be counted as hazardous.

Figure 7: Fibres severely damaged by spark erosion

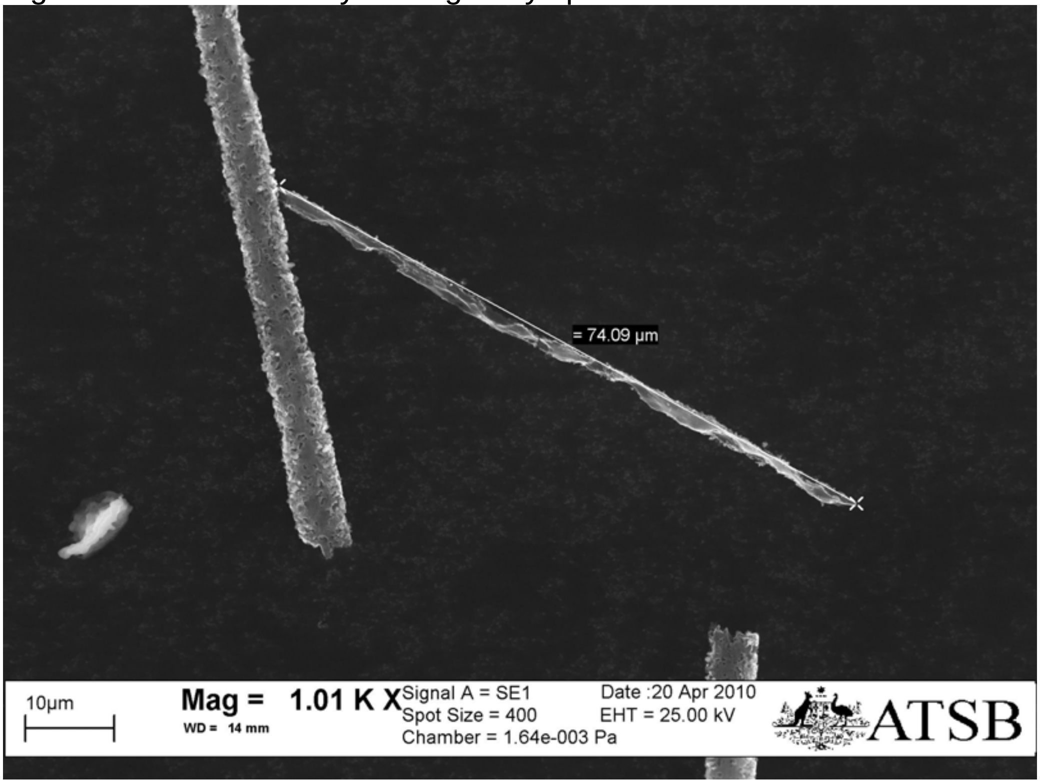
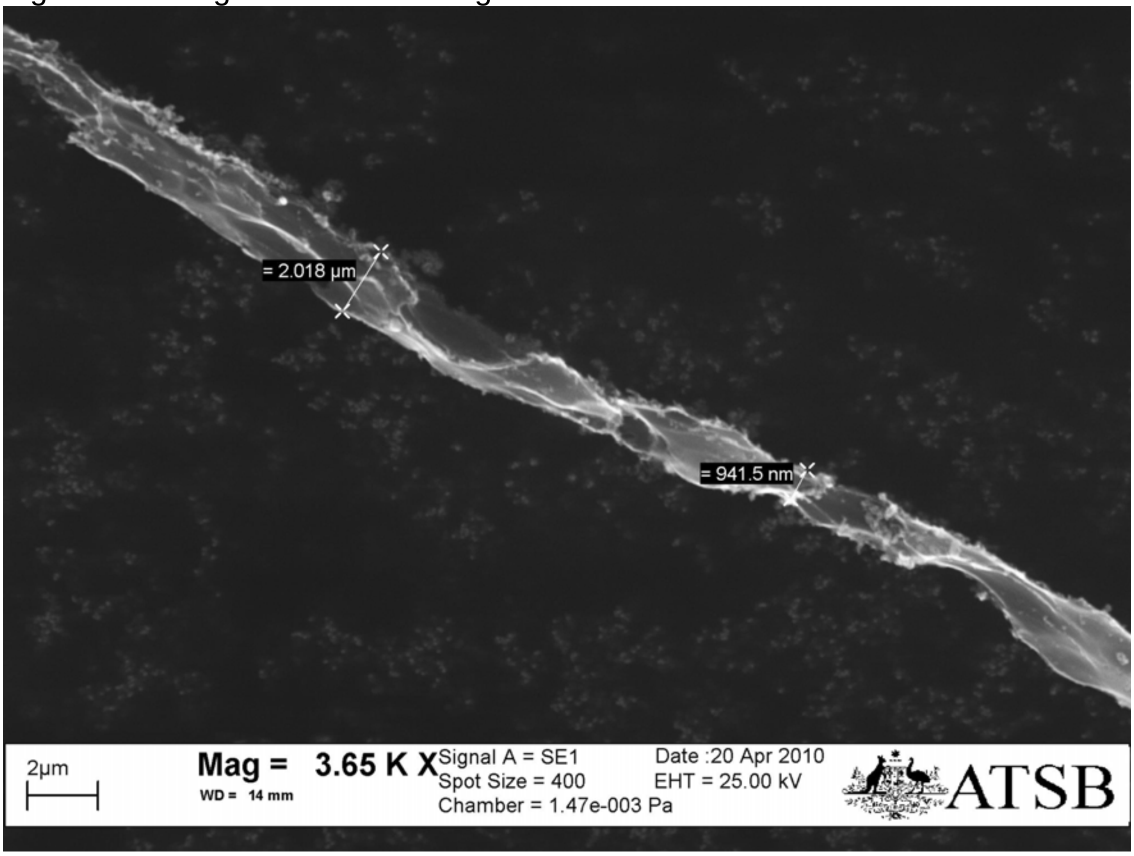


Figure 8: Enlarged section from figure 7



In figure 7 the two fibres in this picture have been severely eroded, the fibre emerging from the top of the image and finishing near the centre is more unusual in having many smaller, deeper holes. A part of the fibre that dominates the centre of figure 7 is shown in greater detail in figure 8. This fibre has been eroded and cratered in a scalloped shape that was common in eroded fibres. The pits are approximately 4 times wider than they are deep, with a pit surface diameter up to 3-4 microns. In figure 7 it can be seen that this fibre is thin enough to appear semi transparent, and curves around on itself like a hollow tube that has been mostly cut away. Although this fibre is too long to be respirable, it is obvious that in places (such as a point slightly to the right of the 2 micron measurement in figure 8,) it would fracture into smaller pieces at the tiniest force, as it is at that, and other points, half a micron or smaller in diameter.

Figure 9: Inspirable fibre

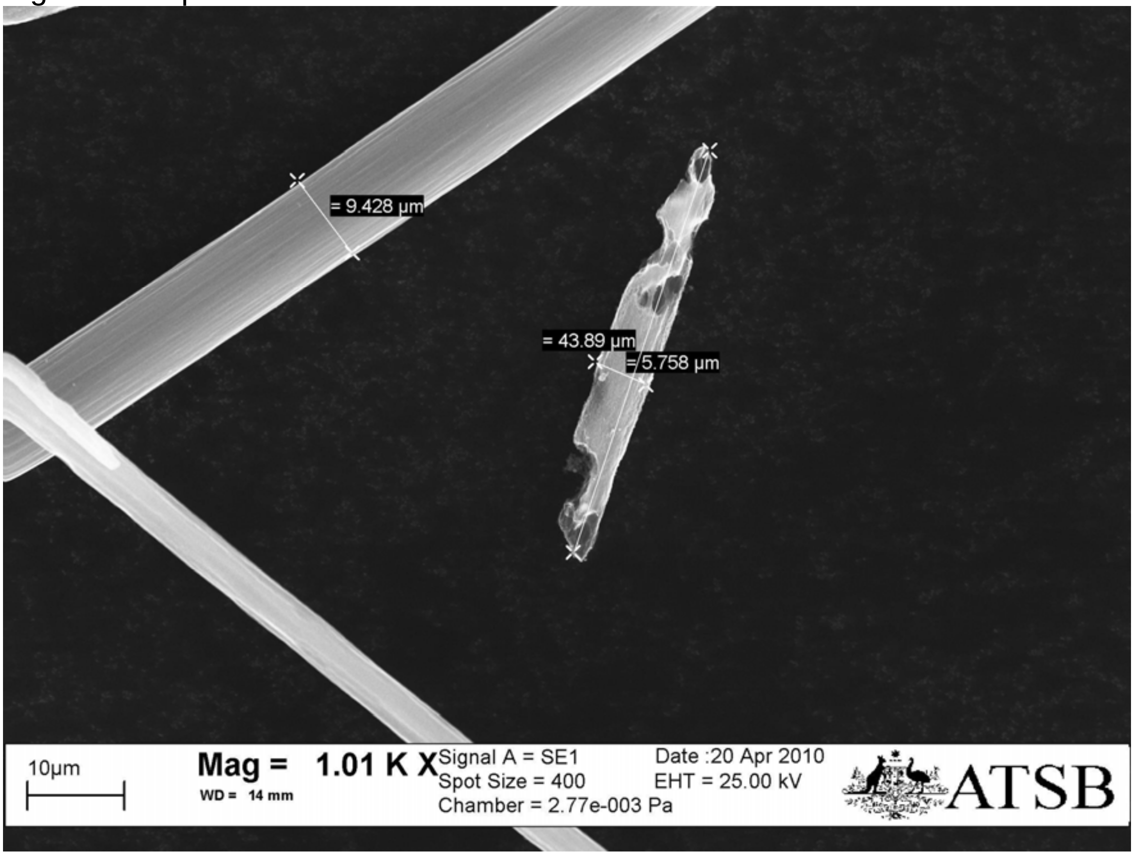


Figure 9 displays an undamaged fibre to the top left which provides a good reference point for the consistently thinned fibre down the bottom. However, by far more fascinating is the fibre dominating the centre of the image. It is pitted with large scallops, but still maintains some structural integrity. Both ends are sharp, with the shape indicating that it broke away from its parent fibre due to excessively large scallops which left it too thin to stay together. An example of this which is yet to happen can be seen in figure 8 However the most interesting part by far is the aspect ratio of 7.6 to 1, placing this, with a diameter of 5 microns and sharp ends as a near perfect example of a inspirable fibre with potentially carcinogenic properties (National occupational health and safety commission, 2005).

1.4 The known dangers

Although carbon fibre is a fascinating and highly useful material it also has its dangers: it is enormously strong but it can break, and when it does break it may be highly dangerous. When an epoxy carbon fibre composite product does break, through tensile overload, it splinters, and these splinters pierce the flesh so dangerously and irreversibly that normal procedure is to quite literally carve out any flesh the splinter may have touched (Australian Transport safety Bureau, 2010).
Research in an informal paper from 2008 on carbon fibre on aircraft crashes revealed that when carbon fibre is simultaneously burned and broken, it

releases significant quantities of fibres that are 2-4 microns long, thus respirable and liberated from the composite, leaving them sharp and rigid (Andrews, p. 1,2, 2008). These fibres have similar physical characteristics to asbestos (Andrews, p. 2,3, 2008). Andrews concluded that when inhaled, these small sharp rigid fibres may stay in the lungs and damage the cells, potentially resulting in chronic lung problems of various severities, or cancer leading to death.
Apart from respirable fibres there are also inspirable fibres to consider, they are 4 to 10 microns in circumference. Although they cannot penetrate as far into the lung as respirable fibres can, they are unlikely to come out of the lung under normal circumstances (Fox, 2010). Any fibres larger than 10 µm usually get lodged in the airway before they reach the lungs (Fox, 2010), to be removed by ciliary movement of mucus along the trachea and bronchus. The sizes of fibres defined as inspirable and respirable are highly varied from source to source, but for the sake of this investigation respirable fibres are considered to be 2-4 microns in diameter, and inspirable fibres are 4-10 microns in diameter. Andrews also found that if carbon fibre is burned and broken, but not simultaneously, then the quantities of dangerous particles released are an order of magnitude smaller (Andrews, p. 1, 2008). However, the funding for that experiment ran out, so no more experimentation was done (Andrews, p. 2, 2008).

A potential risk is that lightning may produce similar damage in carbon fibre composite materials; as lightning provides ample heat to burn the epoxy substrate and more than enough energy to break the carbon fibre. Andrews (2008), notes the potential ongoing impact of respirable carbon fibre particles following the 9/11 tragedy:
“Nearly 40,000 people are estimated to have been exposed to the ensuing hazardous dust and nearly 70% of the emergency services who worked in the area now suffer persistent lung problems, many acute and some have died. Many of the toxic elements of the dust have been identified and discussed but what is not discussed is that it is extremely likely that the release of about 4 or 5 tons of respirable carbon fibres into the dust cloud has contributed to or exacerbated the post crash casualties.” (Andrews, p. 3, 2008)

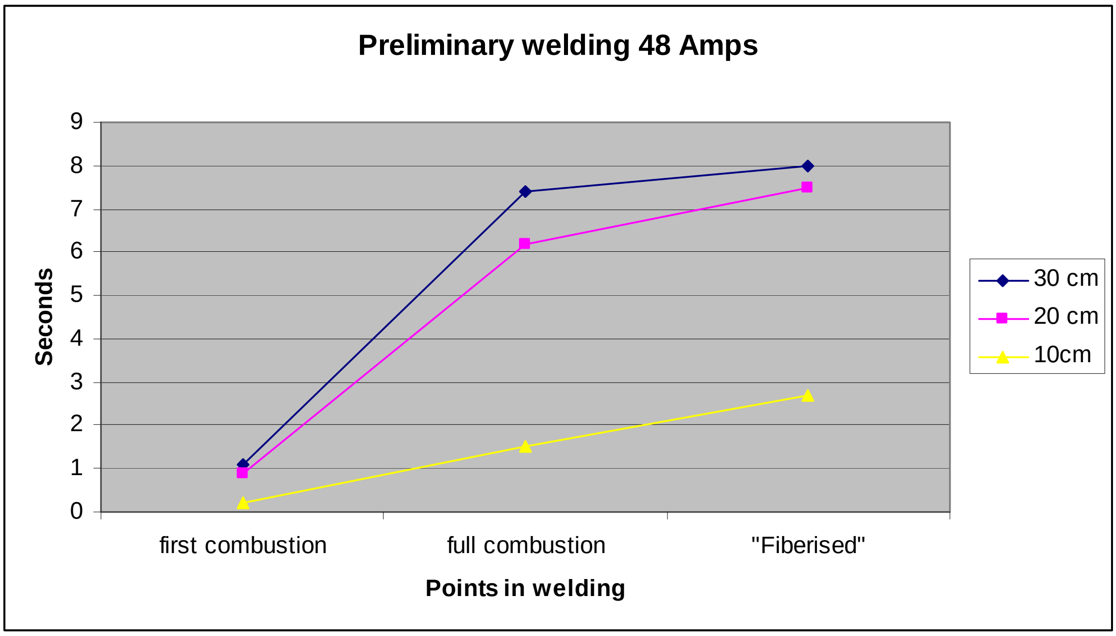
1.5 Lightning

Lightning generators produce high voltages, but have relatively low amps. This means that not only are they harder to control, they also do not do as much damage as shorter, fatter plasma arcs. They are therefore similar to lightning only in appearance, but not in actual effect. Lightning cannot be practically classed as AC or DC current, these are classifications that only really apply to the kinds of electronics used by humans, however the amps provided by lightning are spectacularly large, due to the sheer amount of raw power involved, essentially, the higher the amps the greater the damage (National Lightning Safety Institute, 2010). An arc welder acts as a better substitute than a standard lightning generator. Other tools that employ spark generated plasma of high amps could also substituted, for example other types of welders, or plasma cutters. Arc welders combine the virtues of being available and accessible, controllable, small, portable, consistent and powerful.

1.6 Preliminary testing

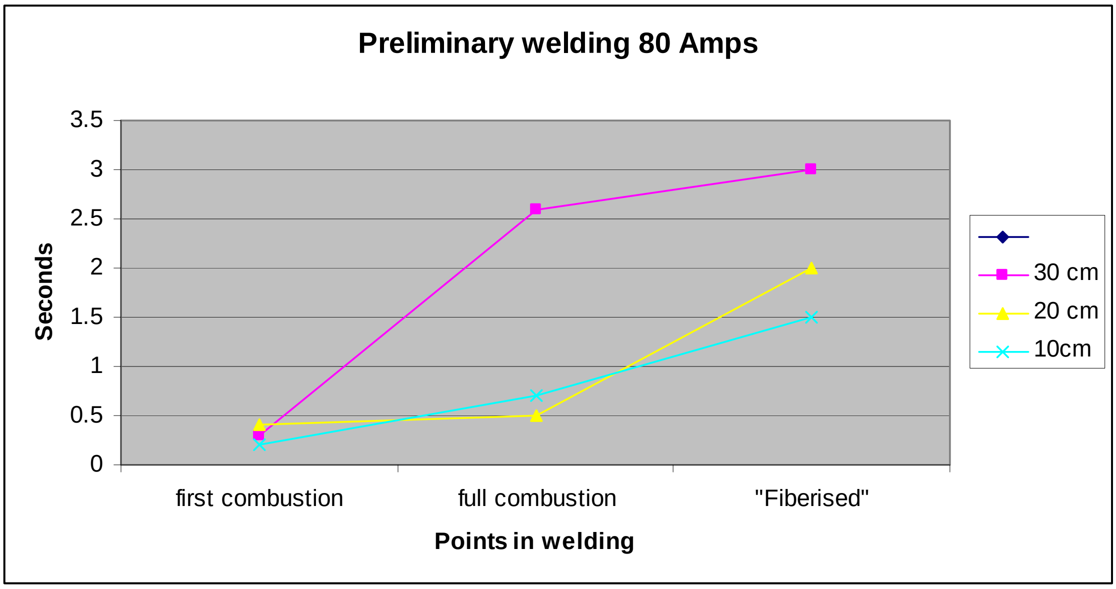
Preliminary testing found the way carbon fibre behaves when subjected to electric current using an arc welder at various lengths and power settings.

Figure 10: Time required to prepare test samples at 48 Amps



Figures 10 and 11 depict the stages of sample preparation when electric current is applied to different lengths of carbon fibre to burn off the epoxy to expose the carbon fibres. First combustion occurs when the epoxy first produces a flame instead of a spark. Full combustion occurs when the entire rod is simultaneously producing flame. “Fiberisation” takes place when the rigid epoxy is burned away enough that the carbon fibre sags or bends and becomes a ponytail of loose fibres. To provide precise measurements, the timing was taken frame by frame from a film. The 130 Amp tests were not performed because it was decided that the reaction was becoming too explosively powerful to be performed without a protective container.

Figure 11: Time required to prepare test samples at 80 Amps



1.7 Equipment

Air samplers are machines which collect a specific volume of air through a filter over a specific time. This means that when you analyse anything collected on the filter, you know the area over which it was collected and with a simple airflow tester you can work the volume of air sampled and calculate how many particles per Litre, millilitre, or Metre^3 (National Occupational Health and Safety Commission, 2005).

Scanning Electron Microscopes, (SEM's),are powerful microscopes that work by creating electrons from a tungsten filament, and then accelerating and focussing them into a collimated beam through the use of electromagnets. They operate under a vacuum with a focusing aperture separating the chamber where the electrons are produced and accelerated, from the chamber where the specimen is placed. The viewing of SEM images can be far more misleading to the casual observer than infrared or ultraviolet or a negative image, because the image is not determined with light in any applicable sense, despite the images and the physical appearance of shape being the same. The apparent colouring, lighting and reflectiveness are determined by the specimen's conductivity and contact with a conductive surface, so something nonconductive like wood or cloth would appear as metallic as mercury, while steel would have about as much sheen as plaster. However, this same metallic appearance provided by non conductive items may prevent specimens from being examinable, because the sheen is caused by a build up of negative charge deposited from the electron beam which repels further electrons; essentially creating a mirror like a bubble around itself. As far as electrons are concerned, even conductive items surrounded by or separated from a conductive surface by non conductive material are nigh impossible to view, for example conductive fibres on a non conductive filter (Silicon Far East, 2005).

1.8 Potential dangers

There is a fear that carbon nanotubes, which are even stronger and even lighter than carbon fibre, may be “the new asbestos” (McCall, 2010) and, although carbon fibre is not as great a threat, the two materials are similar enough to make carbon fibre seem a lot more threatening..

Aircraft are the vehicles most likely to be struck by lightning because of their potential proximity to thunderstorm clouds. Large jet aircraft normally fly above clouds that generate lightning, and small piston engine aircraft normally fly below the level where lightning is most generated. Turbine powered, propeller driven aircraft (commonly called Turboprops) fly at around 20,000 ft, the altitude where most lightning is generated. These aircraft are normally pressurised, and modern Turboprop aircraft may have a significant number of structural components manufactured from carbon fibre composite materials. Turboprops that are approved for passenger carrying are required to have built in lightning conductors that will carry lightning away from composite structural components, however, the lower electrical resistance found in carbon fibre composite compared with other structural fire composites mean there is a greater risk of electrically created damage in carbon fibre composites (Gardiner, 2006).

High performance, amateur built, aircraft may also be manufactured using carbon fibre composites. There are no design requirements for lightning conductors to be built into these airframes. The potential for structural failure caused by damage from an inadvertent lightning strike is correspondingly greater (Lancair, 2007).

1.9 Conclusion

This experiment aims to discover the extent of the airborne hazard caused by inspirable and/or respirable carbon fibres, when a small carbon fibre rod is placed in the spark created by an arc welder. The airborne release from the spark will be captured with an air sampler, and viewed under a Scanning Electron Microscope, to be analysed with a modified comparable equivalent of the standard Australian asbestos sampling method. The results are expected to show high levels of inspirable fibres and present, but low levels of respirable fibres; the levels are expected to be high enough to warrant further research, but not of a great enough concentration to cause great worry.

Hypothesis

Hypothesis
It is hypothesised that if carbon fibre composite releases dangerous levels of respirable and/or inspirable carbon fibres when exposed to spark generated plasma, then if an air sample is taken from a carbon fibre composite that has been eroded using an arc welder, the number of carbon fibres in the 2-10 micron range will be at a concentration of higher than 1 fibre in 10 millilitres of air.

2. Materials

1. 1.5mm carbon fibre rods
2. Arc welder (in this case an ARKO 1615)
3. Air sampler (in this case a Du Pont model P2500A)
4. Scanning Electron Microscope (in this case a Leo 1450 VP)
5. 10 mm SEM stubs
6. Double sided carbon tape
7. Video camera good quality film
8. Empty 800g tin can (dimensions: diameter 9.5cm, height 12.5 cm)
9. Standard caulking gun
10. Rhodorsil V60 Caulk, this could be substituted with another high quality caulk with less electrical conductivity than air (**Not 'liquid Nails'**)
11. Welding plate
12. Welding mask
13. Baking paper non stick (in this case Multix® Bake®)
14. Vegetable oil
15. Drill
16. Tin snips
17. Sticky tape
18. Clamps
19. 2 cartridge filter masks
20. Rotameter air flow meter (in this case from Key Instruments, 0.4-5L)
21. Air sampler filters, 25mm, gridded, 0.8 micron pores, as per safe work Australia's Guidance note on the membrane filter method for estimating airborne asbestos fibres.
22. Compass (geometric)
23. Pencil
24. Ruler

3. Method

3.1 Preliminary test Method

1. Put on a cartridge filter mask with Australian standard 1716 RC 75 cartridges, also wear thick leather gloves and long sleeves, and ensure that you are working in a fume hood or are in an open atmosphere well away from places where humans spend a large amount of time.
2. Set up a camera with fairly high video quality on a tripod pointing at the welding plate, from a distance of at least 2.5 m.

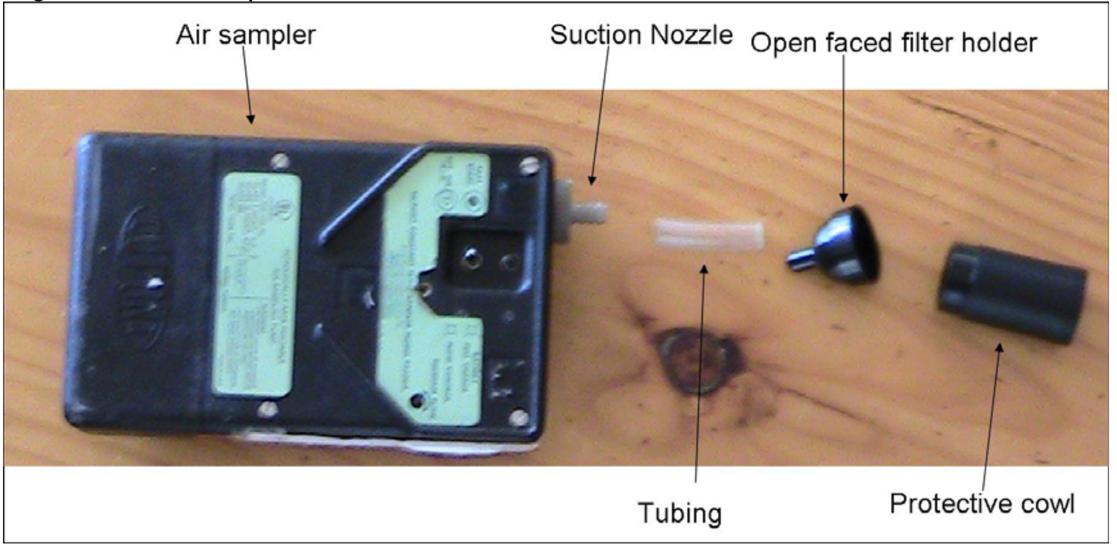
3. Cut a section of carbon fibre of 30, 20 or 10 cm depending on the repetition and clamp it in the welder, also label a zip lock bag to place the final result in for disposal. Put on a welding mask.
4. Start the camera running, clip the grounding clamp onto the welding plate and turn on the welder.
5. Lower the protective flap of the welding mask and place the end of the carbon fibre on the welding plate, being sure to maintain electrical contact to prevent inconsistent results. Depending on the length and power setting, you may be able to see the test specimen clearly through the welding mask but at longer lengths and lower power settings visibility is fairly poor.
6. After a short amount of time you will feel a burst of radiant heat, this is combustion of the epoxy substrate where the entire rod bursts into flame for a few seconds destroying the epoxy. Allow 5 seconds after the first burst of radiant heat to complete “Fiberisation”.
7. After the 5 seconds, remove the carbon fibres from the plate and allow them to hang and cool: often at longer lengths and lower power settings the pony tail of carbon fibres is a little chainlike because it is still matted with charred epoxy. After the fibres have cooled, carefully place them in the zip lock bag making sure that you capture all of the fibres.
8. The repetitions should be performed on your arc welder’s lowest, middle and highest power settings, with the lengths in descending order until all nine combinations have been completed or the reaction becomes too violent to continue.

3.2 Main test Method

1. Use a tin opener to remove one end of the tin. Draw a circle 3cm in diameter on the side of the tin, with the bottom of the circle 1.5 cm from the bottom of the tin. Drill a hole 5mm in diameter near the centre of that circle, then use tin snips to cut out the circle from the can (slightly ragged edges are irrelevant).
2. Take the protective cowl of the sampler and wrap it tightly with non stick cooking paper one layer thick, non stick side outwards. Use sticky tape to attach the paper at the smaller end of the protective cowl. Coat the non sticky taped end of the paper with vegetable oil, clamp it in place with the larger oiled end in the centre of the 3 cm hole. Use the caulk to seal the tin can to the cooking paper around the protective cowl, wait 4 hours.
3. Remove the protective cowl from the cooking paper, then peel the cooking paper away from the caulk attached to the tin, being careful not to remove any caulk with it. The protective cowl ought to seal into the hole while still being removable.
4. Drill a 1 cm diameter hole at the same height as the centre of the 3cm hole 48.5 mm to the right as the crow flies, not around the circumference.

5. Smear a thin layer of caulk around the lower half of the internal half of the tin can that is centred on the drilled hole, to insulate the tin if the carbon fibre curls around and touches the wall.
6. Use an angle grinder to clean the centre of the welding plate to bare metal. Make a thick circle of caulk on the welding plate, (at least 1cm high and wide), the same size as the bottom of the tin,
7. Press the open end of the tin lightly into the caulk circle, making sure that there is still 5mm of caulk between the tin and the welding plate and that there is an airtight seal between the tin and caulk.
8. Drill two 2.5mm diameter holes on the opposite side of the can to the sampling hole 8.5 mm from the edge and 8mm apart to allow an airflow towards the sample filter.
9. Measure as accurately as possible the diameter of the inside of the smaller end of the protective cowl on the air filter inlet, as this determines the exact area over which the sample is collected.
10. Take the protective cowl, the filter holder and the tweezers and sterilize them in boiling water. Carry them with a sterile clean cloth, use a vacuum cleaner with a blow function, or a hairdryer or a heat shrink gun to dry out the sterilized items.
11. Plug the tubing onto the top of the air sampler, then plug the protective cowl including the filter holder into the far end of the tubing. Use the sterilized tweezers to place the filter into the filter holder (grid side up), making sure to prevent the end of the tweezers and the filter from touching anything that isn't sterile. Be particularly careful that you do not take any of the airtight separators that are placed in between each filter paper with the filter paper, as there are sometimes 2 or 3 separators for each filter paper.
12. Plug the protective cowl into its hole in the tin, being careful to not touch the inside or the part that plugs into the filter holder.

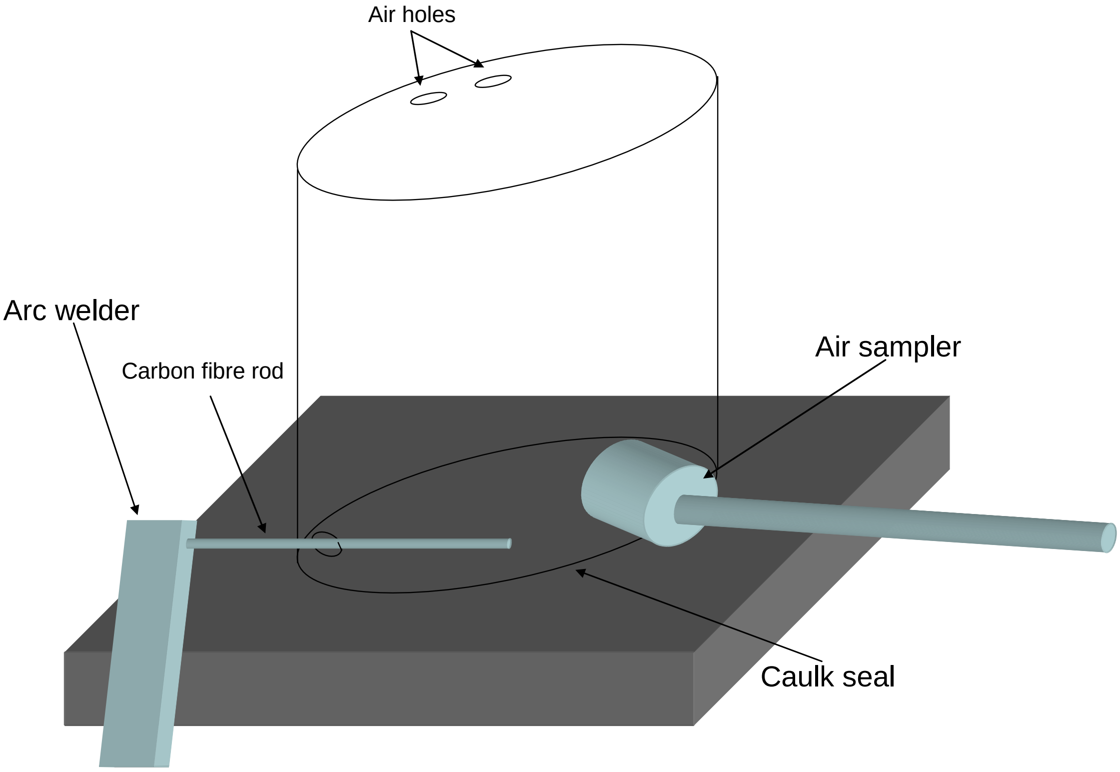
Figure 1: Air sampler



13. Cut a 10 cm section of carbon fibre with a maximum variation of 1.5% (98.5mm-101.5mm) from a 1.5 mm diameter rod .
14. Plug the sampler into the rotameter air flow meter and note the air flow, adjusting it to make it as close to 1Litre per minute (Lpm) as reasonably possible. Make sure that the air flow is within a maximum variation of 5% (0.95 Lpm -1.05 Lpm). Remember to give the air sampler's air flow time to stabilise, place the rotameter air flow meter on a level surface and put your eye at the same level as the silver bead and measure from the centre of the bead.
15. Start the video camera and begin a 9 minute sequence. Leave the air sampler running in the rotameter air flow meter to check that the air flow doesn't vary greatly before you begin sampling.
16. For the 9 minute count down an assistant is required to hold the welder at an open atmosphere location at least 20 m away from any dwelling place. Set the arc welder to 130 Amps. Have the assistant hold an arc welder rod-holder with the 10 cm carbon fibre rod in it as a welding rod. Place the carbon fibre rod though the 1cm hole in the tin, in contact with the welding plate.
17. All people working on the experiment should wear cartridge filter masks with Australian standard 1716 RC 75 cartridges. Make sure that there is no kind of computerised equipment in the vicinity, as loose carbon fibres can be used as a weapon to neutralise and destroy electric equipment or power grids (Centre for Defence Information, 2002).
18. Connect the grounding clamp to the welding plate.
19. Set the welder to its minimum power setting and then quickly tap the top of the tin can with the carbon rod to check that the can is effectively insulated, make sure to do this on every repetition, if a spark occurs on testing then the insulation has failed and the apparatus will require a rebuild.
20. Start a 9 minute count down. Sections 21-25 will relate to times from the start of the count down.

21. 5 seconds in: turn on the welder for 2 seconds to burn off the epoxy with a maximum variation of 0.5 seconds (1.5-2.5 seconds). Be careful to move anything away from the hole where the air sampler will be inserted, as there is often a spurt of flame out of that hole and also make sure that the assistant does not place his/her head over the container, as black smoke escapes through the ventilation holes and it is mildly toxic in large enough quantities and generally unpleasant.
22. 25 seconds in: plug the air sampler into the 3 cm hole in the tin, allow a maximum variation of 2 seconds (23-27seconds) and note the exact second the air sampler was plugged in.
23. 30 seconds in: apply electric current to the carbon fibre sample by turning on the welder, maximum variation < 1 second (must be within the 30th second but not at a specific point within it)
24. 60 seconds in: stop applying electric current to the carbon fibre sample by turning off the welder, maximum variation < 1 second (must be within the 60th second but not at a specific point within it). Disconnect the carbon fibre sample from the welder cable but leave the fibres in the tin by holding the protruding fibres with some pliers then disconnecting the fibres from the welder. Disconnect the grounding clamp from the welding plate.

Figure 2: Tin can setup



25. 9 minutes: turn off the air sampler, maximum variation 1 second (9 min 1 sec – 8 min 59 sec). Re-test the air flow as described in the instructions in step 15. Remove the air sampler protective cowl from the tin and use the tweezers to carefully remove the filter without touching the centre of the filter, and place the filter in a clean container, sampling side up. Seal the container and label it clearly. Store and transport these boxes carefully and the right way up.
26. Use pliers and gloves to remove as many fibres as possible from the sampling tin and place the fibres into an airtight zip lock bag, labelled with the same title as the airtight container in which the filter has been stored. **Do not place the filter holder, protective cowl or tweezers back on the sterile cloth**, carry them in any other way to be re-sterilized but do not replace them on the cloth until the equipment has been cleaned and boiled.
27. Use latex gloves and tap water to rinse and scrub out the tin container. While wearing gloves, put the water in a bucket for appropriate disposal, do not put the water in an ordinary recycling or garbage bin, and definitely do not throw it onto garden/grass/dirt due to the potential long term damage to the flora, fauna and passers by. Use a vacuum cleaner, hairdryer or other air drying equipment to dry out everything, most particularly the caulk around the base of the tin because if there is a water connection between the tin and welding plate then the entire system will short out, probably destroying the tin chamber.
28. Repeat the experiment 10 times, cleaning out and sterilising the appropriate parts in between every repetition. Clean out and dry the

tubing with warm water every second repetition to ensure there is no clogging of the airflow or particles actually entering the sampler.

29. Calculate the percentage airflow change as determined as a percent of the initial as compared to the final measurement with this formula:

    % airflow change from the initial airflow=

$$\frac{\text{(difference between initial Lpm and final Lpm)}}{\text{Initial Lpm}}$$

    Express the decimal result as a percentage. The excel formula is =IF(A<B,(B-A)/A,(A-B)/A) If A=alphanumerical co-ordinates for cell containing initial flow rate (Lpm) and B=alphanumerical co-ordinates for cell containing Final flow rate (Lpm).

30. The formula for calculating the volume of air collected in Litres is thus $(8+{}^{\text{second the air sampler was inserted}}/_{60})\text{x}({}^{\text{Initial flow rate (Lpm)+Final flow rate(Lpm)}})/_{2}$.(The 8 being for the minutes) for example, $(8+{}^{30}/_{60})$x(1.02 Lpm+0.98 Lpm)/2=8.5L
31. The formula for calculating the number of times the container was flushed is: Volume of air collected in Litres/Volume of container in Litres.
32. If any of the maximum variations are exceeded or if the % change of initial Lpm is greater than 5% then that repetition is to be considered null and void.
33. It should be noted that the part of the experiment described in the 9 minute count down is potentially dangerous as carbon fibre when subjected to current suitable for welding may be unpredictable. The samples sometimes react differently due to the smallest variables and it also, by appearance, welds far hotter than its metal counterparts reaching a white hot state that usually indicates 1500+ degrees Celsius in a matter of seconds, so the personal risk should be carefully assessed and mitigated where appropriate before conducting this experiment. For those conducting this experiment with a different sized test chamber, the formula for air collection quantity is simply 10 times the volume of the container rounded up to the nearest litre.

3.3 Scanning Electron Microscope (SEM)

34. SEM examination: your SEM of choice should be operating with a 50 micron aperture. Normal procedure would be to examine the raw filters under variable pressure because the filters are non conductive, however the 100 micron aperture required for variable pressure operation is unable to focus on the filter with air in the chamber, so the following method must be employed.

35. Select all the odd or even samples and place those selected out of the way somewhere safe. Those that were not chosen will be used for SEM examination.
36. Find a large sheet of paper and cover the entire preparation work surface with it.
37. Take five 10mm SEM stubs and place some adhesive conductive carbon tape on top. Trim the edges so the tape stays inside the boundaries of the stub.
38. Remove the non stick layer from the top of the tape.
39. Use forceps to remove the current filter and then firmly press the tape onto the collecting area of the filter, being careful to stick on only half of the filter as depicted by the 1 mm gridlines on the filter.
40. Engrave the stub numbers from 1 to 5 adjacent to the tape and record which filter number has been applied to which stub.
41. Place the stubs in an eight stub holder which is mountable within the SEM, and bring the SEM down to a high vacuum.
42. Focus the SEM and then find a generic area of the carbon tape. Zoom in without moving until you find the magnification which allows you to see 500 microns by 800 microns of unobscured screen (if you can see more then simply don’t use it later) In this case it is 150X, then zoom into 6 or 7 hundred times to focus the microscope, then zoom back out to 500 microns by 800 microns of unobscured screen and the microscope will be focused for a much smaller scale. Usually at this size the automatic scale shown is 100 microns. In the corner of the screen add in a 10 micron measurement and a four micron measurement, remember to only zoom and not move the objective during this process, Take a photo with the highest resolution available (in this case 3072 by 2304 pixels).
43. Take an image at 3 random locations from each filter imprint; also take images of any unusual fibres or phenomenon.
44. It should be noted that there is a good chance that the earliest slide will have a layer of a blue/grey substance on top which is almost certainly vaporised caulk from before the inside of the welding chamber was coated with burned epoxy, the caulk was of course chosen due to its non-conductivity and so will render the entire sample unobservable under the SEM.
45. Print the 800 by 600 micron images on A3 paper making sure that the image is not stretched to fit the paper. Label the images when they are printed off, with the stub number and 1, 2 or 3 depending on where in the order the image was taken.

3.4 Counting

46. Take a compass and draw a circle on a piece of thin card by using the 100 micron scale on one of the printed pictures for the radius, then using the centre and a point at the edge, create a bisected line that will be 50 microns from either point.
47. Use the closest point of the bisected line to draw a circle with a diameter of 100 microns, cut this circle out exactly by hand with a craft knife or scissors. This hole will be used as a graticule for counting fibres on the printed image.
48. Place the first image on a flat surface and then place the circular hole in the paper over a random location on the image. Hold the hole firmly in place and use a pencil or pen to trace obviously around the inside of the circle.
49. Remove the paper circle and check that the drawn circle is visible, then count the number of fibres in the circle according to the criteria from Safe Work Australia's Guidance note (National Occupational Health and Safety Commission, 2005) on the membrane filter method for estimating airborne asbestos fibres.

Counting Criteria

Criteria 1. A countable fibre with both ends within the graticule area shall count as one fibre; a countable fibre with only one end within the area shall count as half a fibre; a fibre with both ends outside the area must not be counted.

Criteria 2. Accuracy for determining fibre length and diameter is critical, and full use must be made of the eyepiece graticule. Estimate the length of curved fibres along the curve of the fibre (that is, true length).

Criteria 4. An agglomerate of fibres, which at one or more points on its length appears to be solid and undivided but which at other points appears to divide into separate strands, is known as a split fibre. Any other agglomerate in which fibres touch or cross one another is known as a bundle.

Criteria 5. A split fibre is regarded as a single countable fibre where the width across the undivided part, not the split part, meets the definition of a countable fibre.

Criteria 6. Fibres in a bundle are counted individually if they can be distinguished sufficiently to determine that they meet the definition of a countable fibre. If no individual fibres can be distinguished as meeting the definition, the bundle is a counted *as a single countable fibre if the bundle as a whole meets the definition of a countable fibre.*

(National Occupational Health and Safety Commission, p. 35, 2005).

50. In this case the definitions of a countable fibre are thus, the fibres are essentially counted in points rather than fibres, discount a point if it is blunt or if its fibre is obviously of a ratio either longer than 20 to 1 or shorter than 3 to 1. Any fibres that are of an even or greater width than the 10 micron measurement should be discounted.
51. Record the number of fibres for this graticule and then proceed. Each image should have 20 graticule measurements equating to 60 measurements per filter.

3.5 Analysis

52. Multiply the total fibres per filter by 1 and 2/3 to produce a figure of fibres/100 graticule areas, this method is a modified equivalent of the asbestos filter membrane method as only an SEM could provide a good enough image of the black carbon fibres surrounded by black soot (with the possible exception of a TEM), and the fibres/ 100 graticule areas figure is a standard figure used with asbestos. The formula is thus: Total Fibres*1 2/3= fibres/100 graticule areas.
53. Calculate the approximate number of dangerous fibres on the filter with the following formula: fibres/100 graticule areas*(PI*Radius of inside of protective cowl in microns^2) /(PI*50 microns^2)
54. From here create a figure for fibres per ml however note that due to the contained nature of the tin and the fact that the tin was flushed through with air 10 times the figure is not applicable effectively with OH&S standards, but it provides a good reference for comparison with similar experiments, the formula is thus: Fibres on filter/(Litres of air collected*1000)= Fibres.
55. The formula for calculating the minimum possible average concentration of airborne fibres in the tin can chamber is (F/ml)*number of times chamber was flushed through.
56. The formula for calculating the quantity of air required to dilute the sample to a safe level if assuming similarity to more dangerous forms of asbestos as according to National Occupational Health and Safety Commission, (1995) levels for Asbestos (Litres) is (Fibres in collecting area of sample/100).
57. The formula calculating the minimum possible times of the sustainably safe level in the can (F/ml) if assuming similarity to more dangerous forms of asbestos as according to National Occupational Health and Safety Commission, (1995) levels for Asbestos is: Minimum possible average concentration of airborne fibres in the tin can chamber (F/ml)*10.

3.6 Preliminary Examination

1. Use a SEM (in this experiment a Leo 1450 VP SEM was used but any reasonably modern SEM will substitute). For a control, mount and view a set of fibres where the epoxy substrate has been removed by the application of a high current through the carbon fibre, but has not been exposed to subsequent continuous high current.
2. Take a 10 mm SEM stub and place some double sided carbon tape on top, (these are common but specialised materials specifically for SEM's) quickly and carefully open the zip lock bag and apply the carbon tape to the contaminated face of a filter paper to pick up the sample for examination.
3. Mount the 10 mm SEM stub in the SEM and examine the fibres under high vacuum, as all the materials are conductive. Search for fibres that have been particularly damaged by the spark generated plasma, the ones to look for are those which have been particularly pitted or thinned, the ones of particular interest are those which are short, sharp and eroded to become thinned like Figure 7 on page 14. These fibres best match the physical criteria for hazardous asbestos fibres.
4. Provide a control by repeating the process with the sample from the preliminary testing that appears the most consistent, smooth and silky. Cut a small section from the pony tail and examine it to check that the test carbon fibres do not usually display any properties you have discovered on the previous test/repetition.

3.7 Risk assessment

The two main risks are:

1. The arc welder: the danger from ordinary use, the danger from its reaction with the carbon fibre rod and the danger from any fumes released are all mitigated by the welder being used within the tin can setup with the air sampler providing suction.
2. The dust samples: which are potentially deadly if inhaled can be prevented from inhalation by wearing a cartridge filter mask and by working in an outdoors environment that provides a breeze to remove any accidentally released fibres which will be diluted into the atmosphere to a safe level.

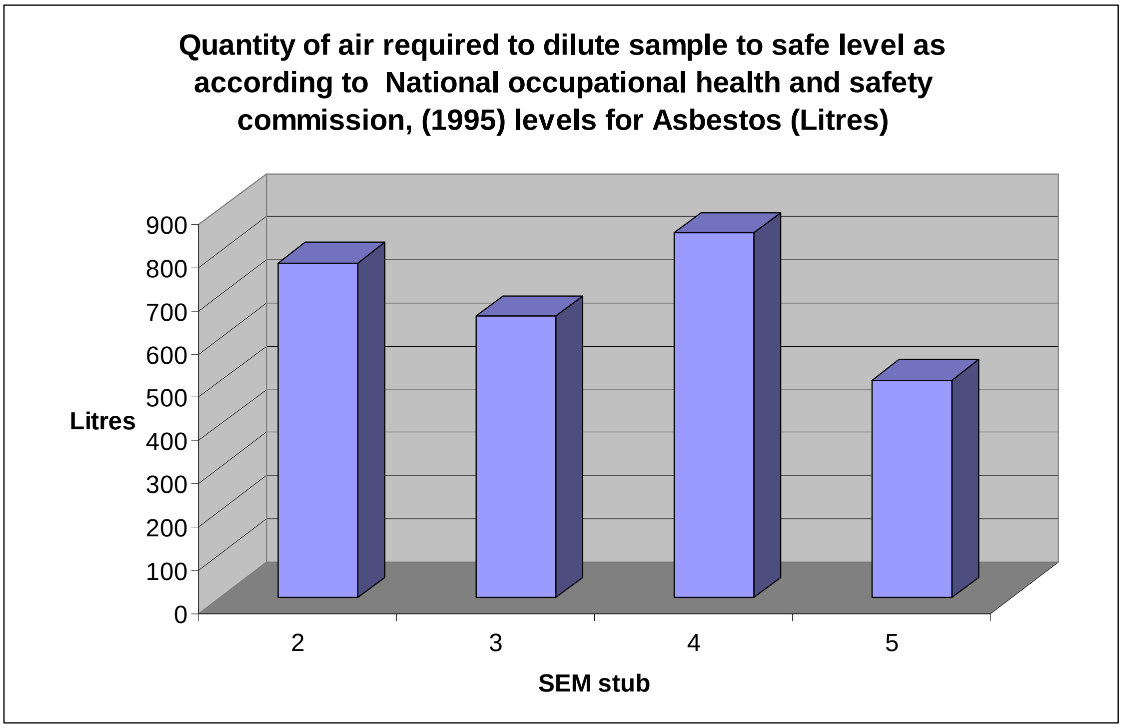
ime in minutes	Initial flow rate (Lpm)	Final flow rate (Lpm)	% change of initial flow rate	Volume of air collected (L)	Diameter	Volume of container in Litres	Number of container cycles	Total fibres on graticules	Fibres per 100 graticules	Fibres in collecting area of sample	F/ml
0.05	1.01	1	0.99%	0.05025	21.1mm	1.07	0.046963	N/A	N/A	N/A	N/A
0.31666667	0.98	1.02	4.08%	0.316666667	21.1mm	1.07	0.29595	N/A	N/A	N/A	N/A
f plastic											
0.333333333	1.01	0.97	3.96%	0.33	21.1mm	0.335	0.985075	N/A	N/A	N/A	N/A
on											
3.8	1.00	1.04	4.00%	3.876	21.1mm	0.335	11.57015	N/A	N/A	N/A	N/A
1.83333333	0.97	0.99	2.06%	1.796666667	21.1mm	0.335	5.363184	N/A	N/A	N/A	N/A
8.6	0.96	1	4.17%	8.428	21.1mm	0.867	9.720877	N/A	N/A	N/A	N/A
ded to provide final prototype											
8.61666667	1.02	0.99	2.94%	8.65975	21.1mm	0.886	9.773984	N/A	N/A	N/A	N/A
8.58333333	0.98	0.99	1.02%	8.454583333	21.1mm	0.886	9.542419	N/A	N/A	N/A	N/A
8.56666667	1.04	0.99	4.81%	8.695166667	21.1mm	0.886	9.813958	104.5	174.1667	77540.74	8.918
2.5	0.95	0.99	4.21%	2.425	21.1mm	0.886	2.73702	N/A	N/A	N/A	N/A
8.56666667	1.05	1	4.76%	8.780833333	21.1mm	0.886	9.910647	N/A	N/A	N/A	N/A
8.55	1.03	1.01	1.94%	8.721	21.1mm	0.886	9.843115	88	146.6667	65297.47	7.487
8.6	0.97	0.98	1.03%	8.385	21.1mm	0.886	9.463883	N/A	N/A	N/A	N/A
8.55	0.98	1.02	4.08%	8.55	21.1mm	0.886	9.650113	N/A	N/A	N/A	N/A
8.61666667	1.01	0.97	3.96%	8.5305	21.1mm	0.886	9.628104	114	190	84589.9	9.916
8.56666667	1.02	1.04	1.96%	8.823666667	21.1mm	0.886	9.958992	N/A	N/A	N/A	N/A
8.6	1.01	1.01	0.00%	8.686	21.1mm	0.886	9.803612	68	113.3333	50457.13	5.809
8.58333333	0.99	1.01	2.02%	8.583333333	21.1mm	0.886	9.687735	N/A	N/A	N/A	N/A
6.21296296	1.00	1.001111	2.89%	6.227356481	21.1mm	0.813556	7.655321	93.625	156.0417	69471.31	8.033

The following results are based around the fibre counts provided by the 800 by 600 hundred micron images.
Any references to the safe levels as according to National Occupational Health and Safety Commission, (NOHSC) 1995 are following the assumption that the safe levels are very similar to that of their most similar airborne fibres; the more dangerous forms of asbestos.

Table 2 Fibre count results

Total fibres on graticules	Fibres per 100 graticules	Fibres in collecting area of sample	F/ml	Minimum possible concentration of fibres in tin can (F/ml)	Quantity of air required to dilute sample to safe level as according to National occupational health and safety commission, (1995) levels for Asbestos (Litres)	SEM stub
104.5	174.16666	77540.74167	8.91768	87.51776712	775.4074	2
88	146.66666	65297.46667	7.48738	73.69917231	652.9747	3
114	190	84589.9	9.91617	95.47392777	845.899	4
68	113.33333	50457.13333	5.80901	56.94936042	504.5713	5

Figure 1: Dilution of carbon fibres



Discussion

Many of the figures in the results are frighteningly large (the minimum possible concentration of fibres within the tin were up to 955 times the sustainably safe levels, (National Occupational Health and Safety Commission, 1995). This is because the experimental design concentrates the carbon fibres so that they may be collected more easily: the tin can setup had a low volume, therefore a great majority of the fibres were collected; probably greater than 95%. Far more air was passed through the can than the can could contain, therefore all the fibres were contained in a volume less than one ninth of the volume that passed through the filter, meaning that any calculation of fibres per millilitre based on the raw data from this experiment would be flawed, but produce a good reference point to work from, to compare with and create more relevant figures. The results produced are in and of themselves enough to justify further research; the fundamental questions behind the research have both proven positive:

- One, does carbon fibre produce dangerous respirable and/or inspirable particles when placed in a plasma arc? Yes, both.
- Two, does it produce these materials in great enough quantities to be dangerous? Definitely, but under unrealistic laboratory conditions.

In relation to lightning strikes producing these fibres, which were what this experiment was originally aiming to discover, this experiment has demonstrated the possibility that hazardous carbon fibres could be released if lightning struck composite carbon fibre products. However, this experiment did not, and could not, simulate lightning accurately enough to provide a realistic simulation.

Perhaps it was the duration that the carbon fibres were eroded that created the potentially hazardous fibres. Per/haps it is because the heat or electrical power of the lightning is so much greater than an arc welder that it destroys the fibres the way the welder destroys the epoxy substrate. There are far too many variables. Only with testing with a lightning rod or a machine that simulates lightning with power in the same order of magnitude as lightning could a realistic simulation happen.

Carbon fibres are relatively indestructible: even if they break into shorter sections, they remain uniform and near perfect in cross section unless exposed to extremely corrosive conditions, retaining their qualities as in figure 15, page 65, whether they are physically broken or even burned, they simply become shorter.

Given this, this experiment's findings about the degradation of carbon fibre when exposed to strong current were extraordinary. A great variety of degradations of the carbon fibre were observed and none of them complied with the usual observations as stated above: instead there seemed to be a uniform beginning of small craters all around the surface of the fibre, leaving the surface with a pockmarked, moon like appearance but only incrementally compromising the fibre's structural integrity. Then there was a short phase in which the pockmarked erosion continued until the fibres had a very square cross section, suggesting that the PAN production method somehow made the fibres more vulnerable to eroding in squares, but yet again the fibres were not sharp and only partially structurally compromised. The next stage seemed to take far longer and many more examples of it were seen. In this stage large chunks of the fibre were seemingly carved out, creating almost spoon shaped holes, leaving the carbon fibre with large chunks missing, sometimes spanning almost the entire width of the remaining fibre. This part of the process leaves the microstructure greatly compromised, often to the point that the fibre cannot even remain intact let alone withstand tension.

Within the airborne samples but not the preliminary tests, there were fibres that had, from their appearance, simply split off the larger fibre like splinters. These comprised the majority of the airborne fibres. It is surmised that the fibres that were actually in contact with the welding plate split off like this due to the more corrosive environment at the point of contact.

The last major variety in the erosion that occurred is that displayed in figure 5 in page 12. These feathers within the fairly normal crater were a phenomenon not observed anywhere else in the experiment or preliminary testing and had potential for further research. Indeed, each one of the unusual and unexpected erosions just described have a potential for further research to help understand this material better, as it is playing a larger and larger part in our modern world.

From an Occupational Health and Safety point of view, the levels of dangerous fibres were high enough to warrant more rigorous testing on the levels produced in a realistic environment, with a greater volume of carbon fibre destroyed. Perhaps tests on standard AC current damaging carbon fibre. From an aviation point of view, this experiment could justify tests with a relatively accurate lightning simulation.
If the experiment was to be improved, the main differences would be that the chamber would be larger and relatively heat proof, with it the entire experiment would be scaled up to essentially simulate a room, and the sample size that actually made it to the final results would be at least 20.

An extraneous finding of this study, was that potential for damage occurred when a high current created heat from the semi-conducting properties of the carbon fibres, (approximately one ohm per centimetre in the test sample), leading to spontaneous combustion of the epoxy substrate. In an aircraft accident initiated by a lightning strike, this mechanism would lead to a more acute problem caused by a loss of airframe structural integrity, compared with the risk of inhaling toxic fibres.

It was found that the fibre counts were relatively high when compared with the levels and counts usually found in asbestos and the levels for the dangerous particles were very high. For comparisons sake according to National Occupational Health and Safety Commission, (1995) the safe levels for regular exposure to the more dangerous forms of asbestos is 1 fibre in 10ml of air, and this is what the carbon fibres are being compared with. The data set for stub 5 should not be considered as very accurate, because this sample was partially obscured by large quantities of soot of unknown composition.

Figure 1 shows the quantity of air required to dilute the fibres down to the safe level of 0.1F/ml, in sample number 4 the quantity of air required to dilute the fibres produced from a very small percentage of a 1.5 mm carbon fibre rod required 846 L to reduce the concentration to a level deemed safe by NOHSC.

A majority of the dangerous fibres produced can be explained by an unexpected phenomenon where the fibres seemingly split like a splinter from a log and produce dangerous inspirable and respirable fibres, as is demonstrated in figure 2, where a fibre had just, or was in the process of splitting.

Conclusion

In conclusion, a plasma arc can damage and erode carbon fibre to release airborne fibres that show the same physical characteristics of inspirable/respirable asbestos fibres, by meeting the criteria for aspect ratio and for being both sharp and rigid. The experiment failed to disprove the hypothesis.
The levels of airborne fibres that showed characteristics of asbestos within the tin were up to 955 times the level of the more dangerous types of asbestos that can be continuously breathed without any long term health implications, and an average of 784 times.

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Mike Watson, from the Australian Transport Safety Bureau, my father, who was a driving force right from the very beginning of this project, gave up countless hours to assist and who was involved in some way in every single step of the process.

Appendix

Table 1 Preliminary welding 48 Amps

preliminary 48 amps	30 cm	20 cm	10cm
first combustion	1.1	0.9	0.2
full combustion	7.4	6.2	1.5
"Fiberised"	8	7.5	2.7

Figure 1 Preliminary welding 48 Amps

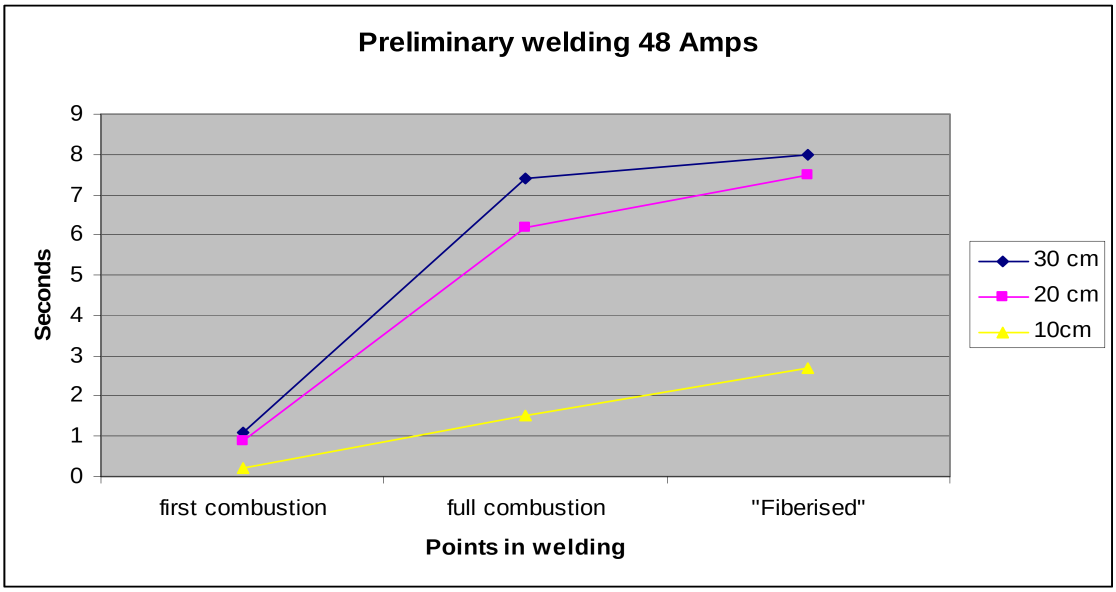


Table 2 Preliminary welding 80 Amps

preliminary 80 Amps	30 cm	20 cm	10cm
first combustion	0.3	0.4	0.2
full combustion	2.6	0.5	0.7
"Fiberised"	3	2	1.5

Figure 2 Preliminary welding 80 Amps

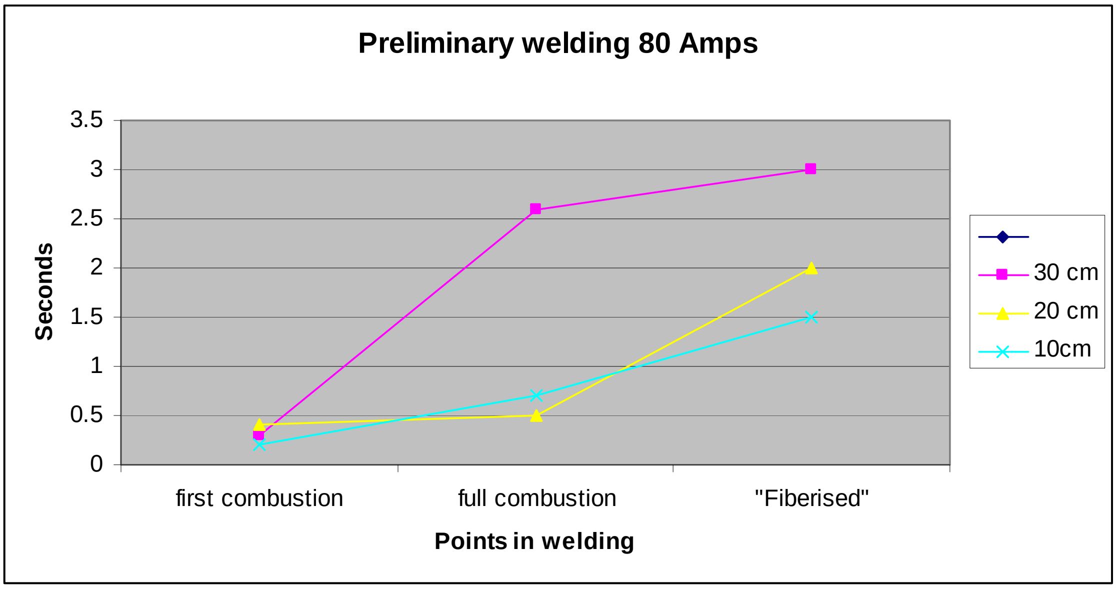
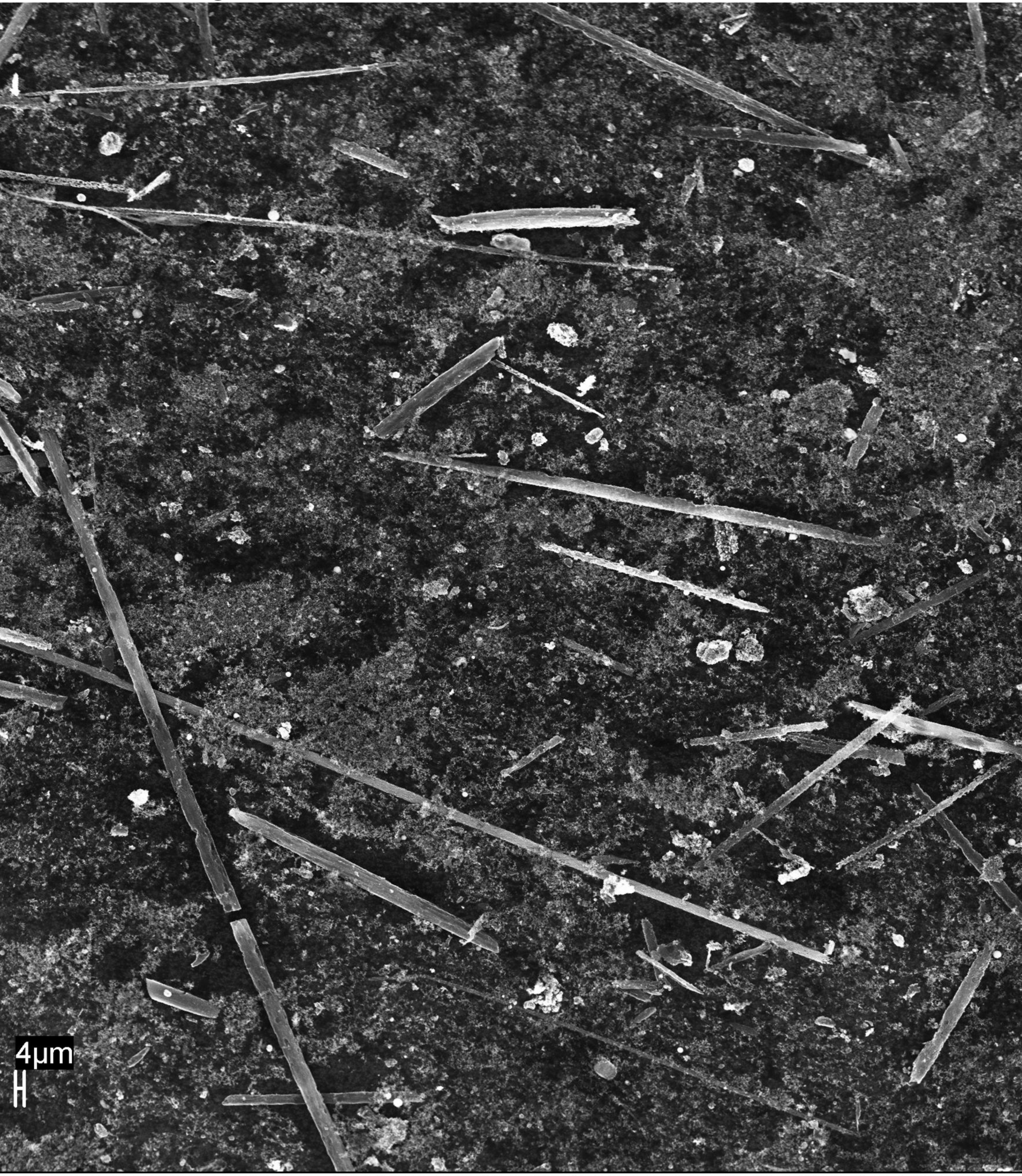


Table 3, Stub 2, graticules

Graticule	Fibres	Image
1	2.5	2,1
2	1.5	
3	1.5	
4	1	
5	2	
6	1	
7	1	
8	2	
9	2	
10	1	
11	2	
12	1	
13	1.5	
14	1	
15	1.5	
16	2	
17	3	
18	2	
19	0	
20	2	
21	2	2,2
22	2.5	
23	2	
24	2	
25	2	
26	3	
27	1	
28	3.5	
29	0.5	
30	1.5	
31	1.5	
32	2.5	
33	2	
34	4	
35	3	
36	2.5	
37	3.5	
38	2	
39	3.5	
40	0.5	
41	1	2,3
42	2	
43	1.5	
44	3.5	
45	0.5	
46	1.5	
47	0	
48	0.5	
49	3	

	50	1
	51	1.5
	52	1.5
	53	2
	54	1
	55	1
	56	0.5
	57	2.5
	58	0.5
	59	0.5
	60	2.5
total		104.5

3: SEM Image 2,1



Mag = 150 X

WD = 17 mm

Signal A = SE1

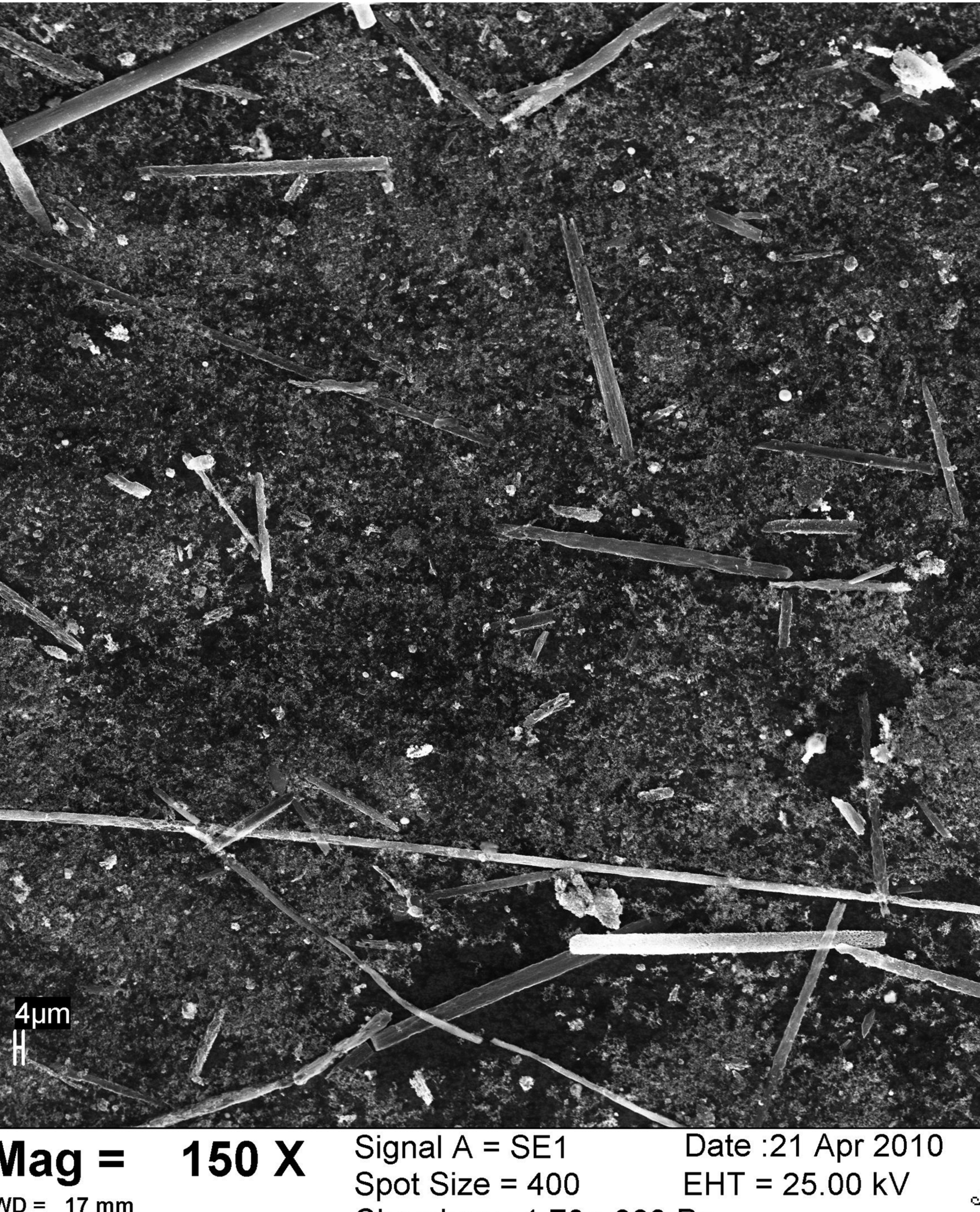
Spot Size = 400

Chamber = 2.10e-003 Pa

Date :21 Apr 2010

EHT = 25.00 kV

4: SEM Image 2,2



5: SEM Image 2,3

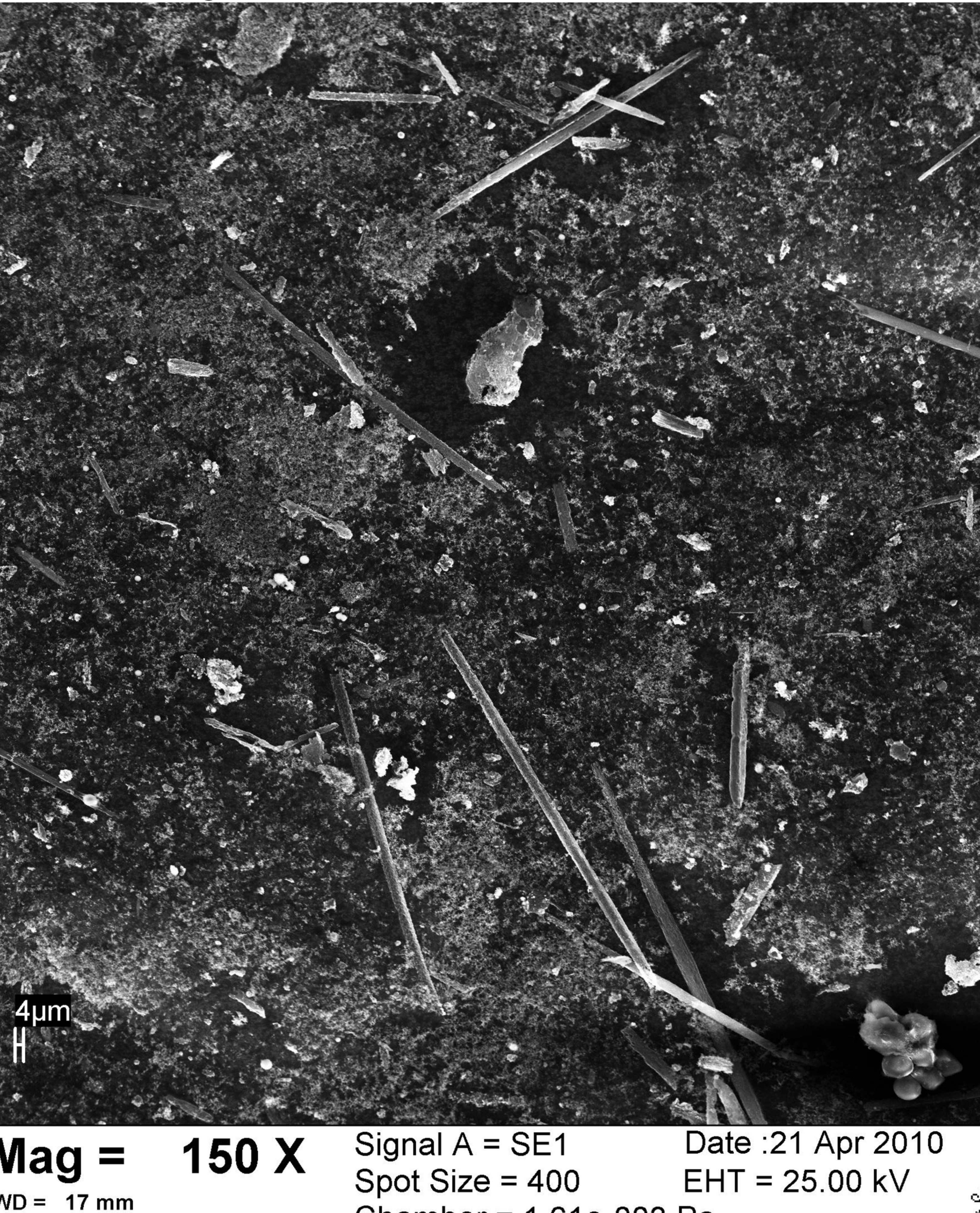
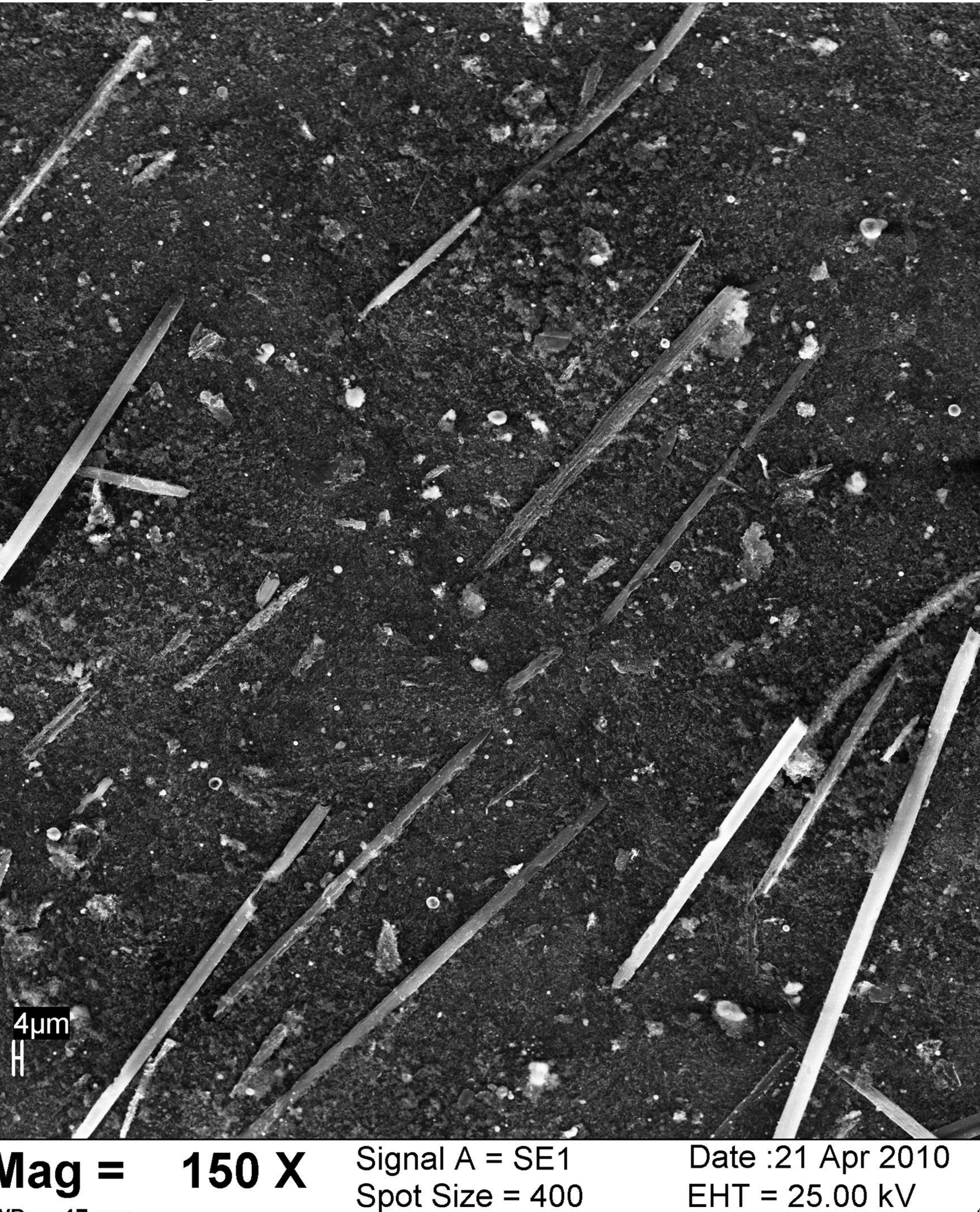


Table 4, Stub 3, graticules

Graticule	Fibres	Image
1	2.5	3,1
2	1	
3	2	
4	0.5	
5	1	
6	2	
7	2	
8	1.5	
9	2	
10	1	
11	2.5	
12	2.5	
13	2.5	
14	0.5	
15	2.5	
16	1	
17	1.5	
18	0.5	
19	1	
20	1.5	
21	2	3,2
22	4.5	
23	1.5	
24	1	
25	1.5	
26	0	
27	1.5	
28	2	
29	1.5	
30	1	
31	0.5	
32	0.5	
33	1	
34	1	
35	1.5	
36	2.5	
37	1.5	
38	1	
39	1.5	
40	3.5	
41	2	3,3
42	2	
43	2.5	
44	0	
45	0	
46	1	
47	1	
48	0	

	49	1.5
	50	2.5
	51	0.5
	52	1
	53	1
	54	1
	55	2.5
	56	1
	57	0.5
	58	1.5
	59	1.5
	60	2.5
total		88

6: SEM Image 3,1



7: SEM Image 3,2

Mag = 150 X
WD = 17 mm

Signal A = SE1
Spot Size = 400

Date :21 Apr 2010
EHT = 25.00 kV

3: SEM Image 3,3

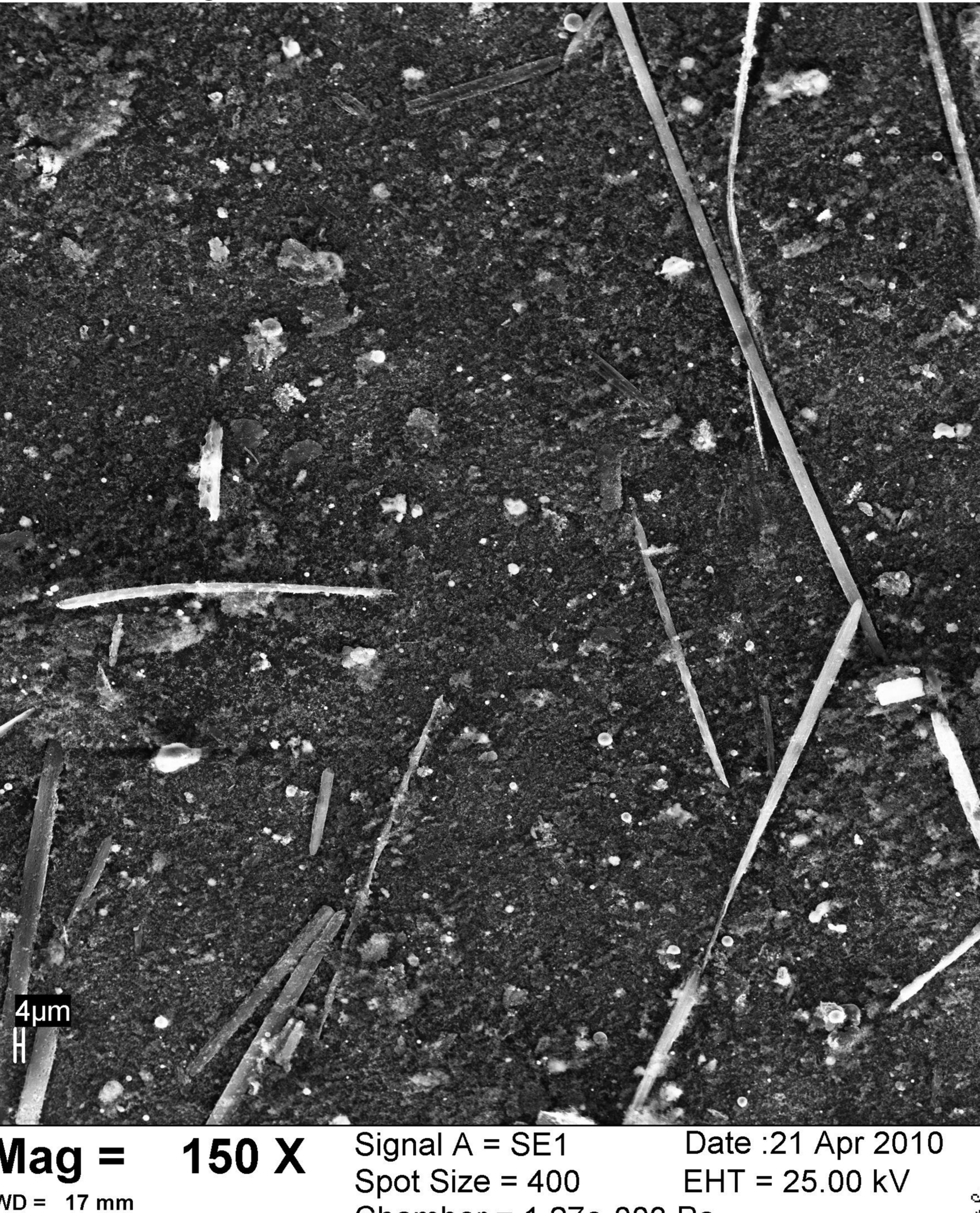


Table 5, Stub 4, graticules

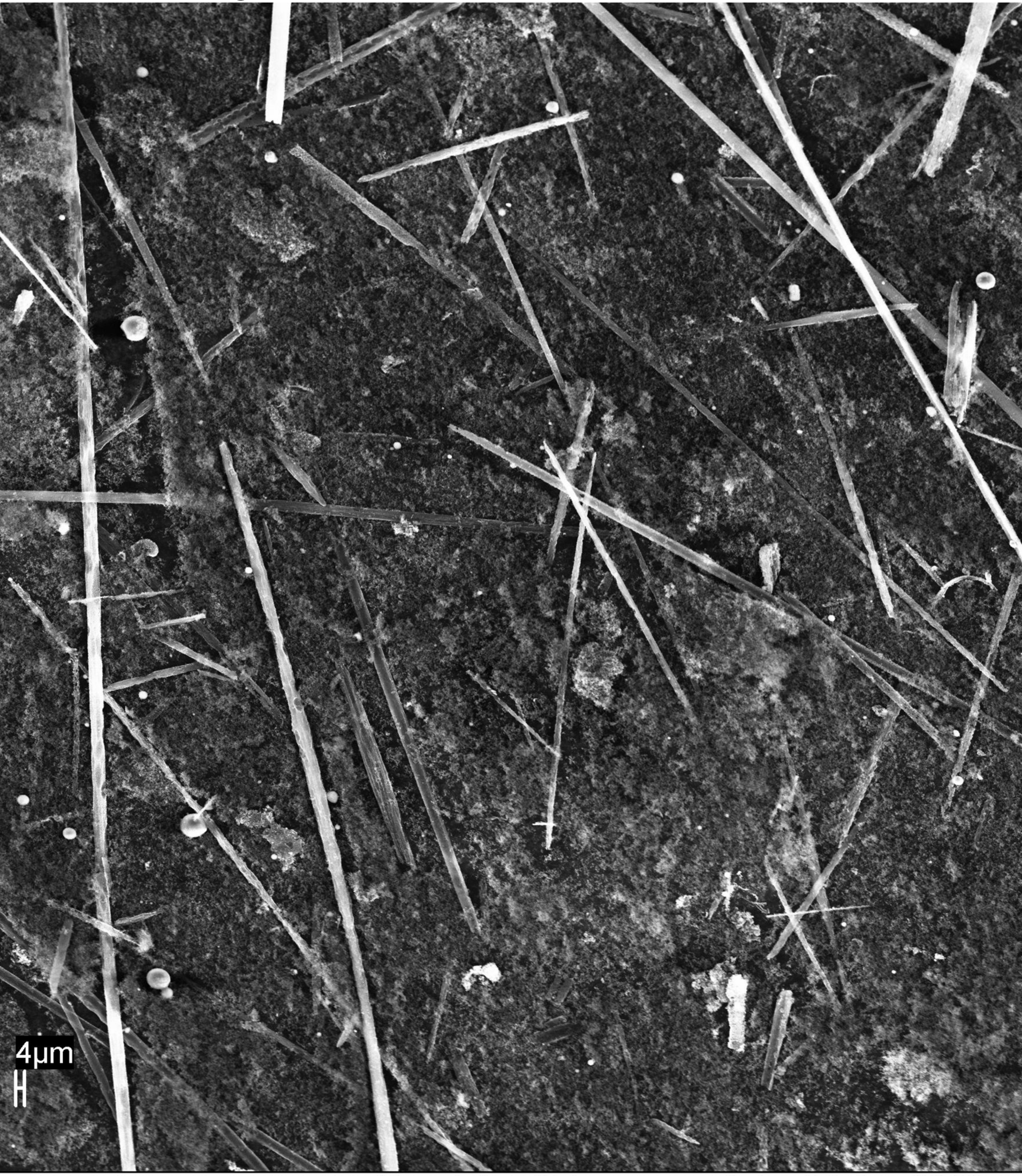
Graticule	Fibres	Image
1	1.5	4,1
2	0.5	
3	1.5	
4	1	
5	0.5	
6	0	
7	2	
8	2	
9	1	
10	2.5	
11	1.5	
12	0	
13	2.5	
14	2.5	
15	2	
16	2.5	
17	0.5	
18	1	
19	0.5	
20	2	
21	0.5	4,2
22	2	
23	3	
24	2.5	
25	2	
26	0	
27	1	
28	3.5	
29	2.5	
30	3.5	
31	3.5	
32	2	
33	3	
34	2.5	
35	3	
36	5.5	
37	2	
38	3	
39	0.5	
40	2.5	
41	2	4,3
42	2	
43	1.5	
44	3	
45	2	
46	1	
47	1	
48	1.5	
49	0.5	

	50	0
	51	2
	52	1.5
	53	1.5
	54	3.5
	55	2
	56	4.5
	57	2.5
	58	3.5
	59	2
	60	1
total		114

9: SEM Image 4,1

10: SEM Image 4,2

11: SEM Image 4,3



Mag = 150 X

WD = 18 mm

Signal A = SE1

Spot Size = 400

Chamber = 1.05e-003 Pa

Date :21 Apr 2010

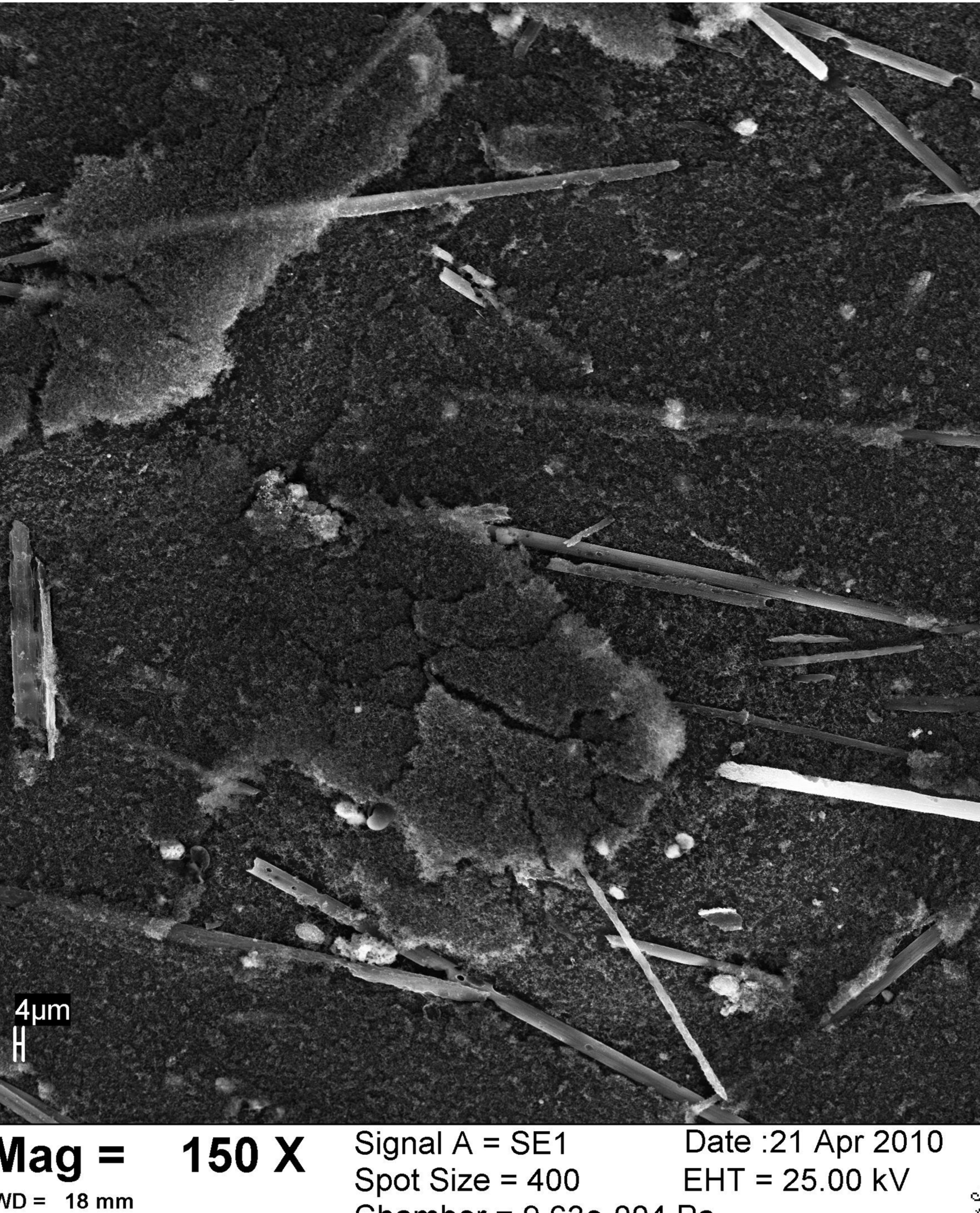
EHT = 25.00 kV

Table 6, Stub 5, graticules

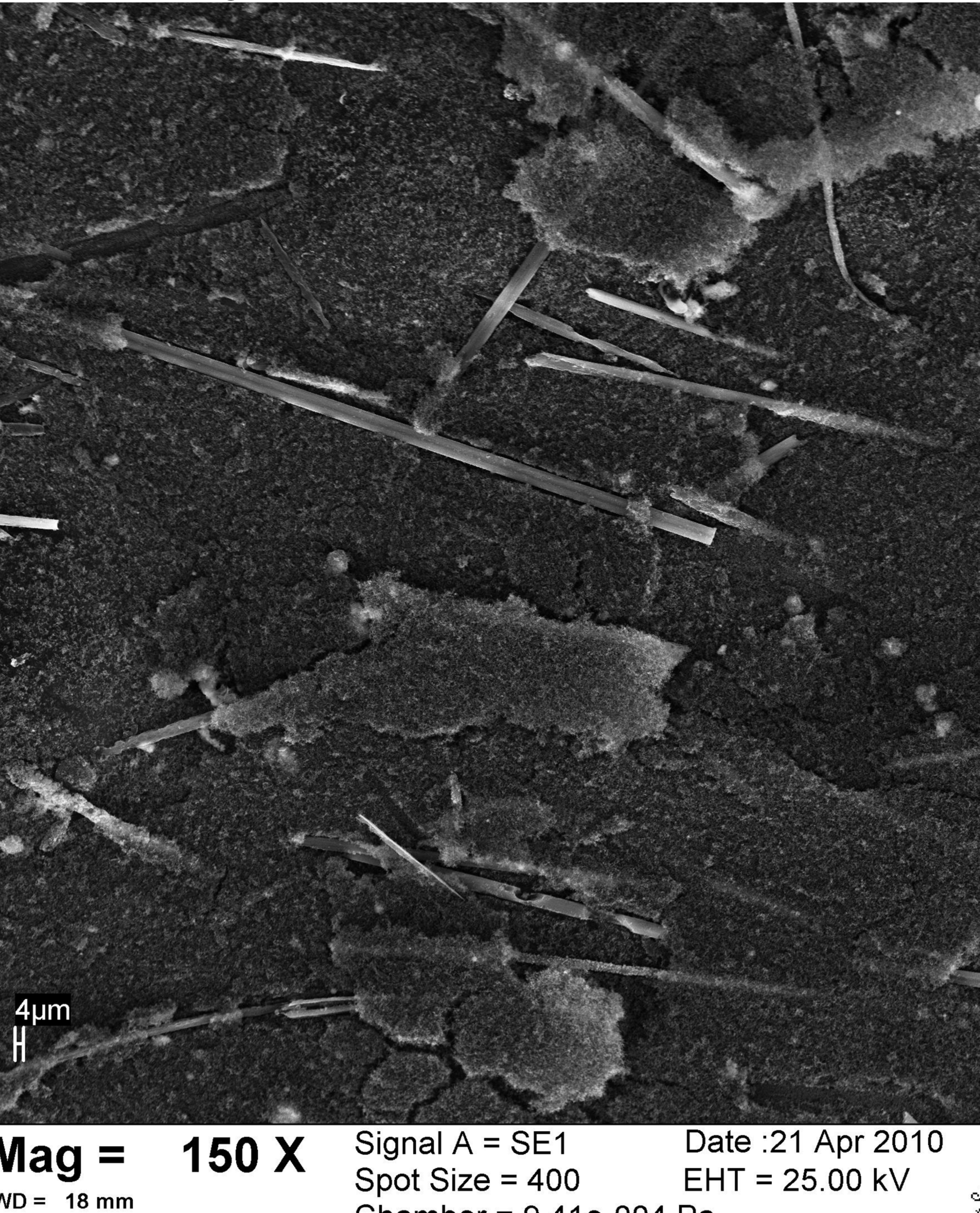
Graticule	Fibres	Image
1	1.5	5,1
2	0.5	
3	1	
4	0.5	
5	2.5	
6	0.5	
7	0.5	
8	2.5	
9	1	
10	1.5	
11	2	
12	1	
13	1	
14	1.5	
15	0	
16	2	
17	2.5	
18	2	
19	1	
20	0.5	
21	3	5,2
22	2.5	
23	1	
24	3	
25	1.5	
26	1	
27	0.5	
28	1	
29	0.5	
30	1	
31	2.5	
32	0.5	
33	1.5	
34	1	
35	1.5	
36	0.5	
37	0	
38	1	
39	0.5	
40	0.5	
41	1	5,3
42	1	
43	2	
44	0.5	
45	2.5	
46	1	
47	0	
48	1	
49	0	

50	0
51	0
52	1
53	0
54	0.5
55	1
56	1.5
57	1
58	2.5
59	1
60	0.5
total	68

12: SEM Image 5,1



13: SEM Image 5,2



14: SEM Image 5,3

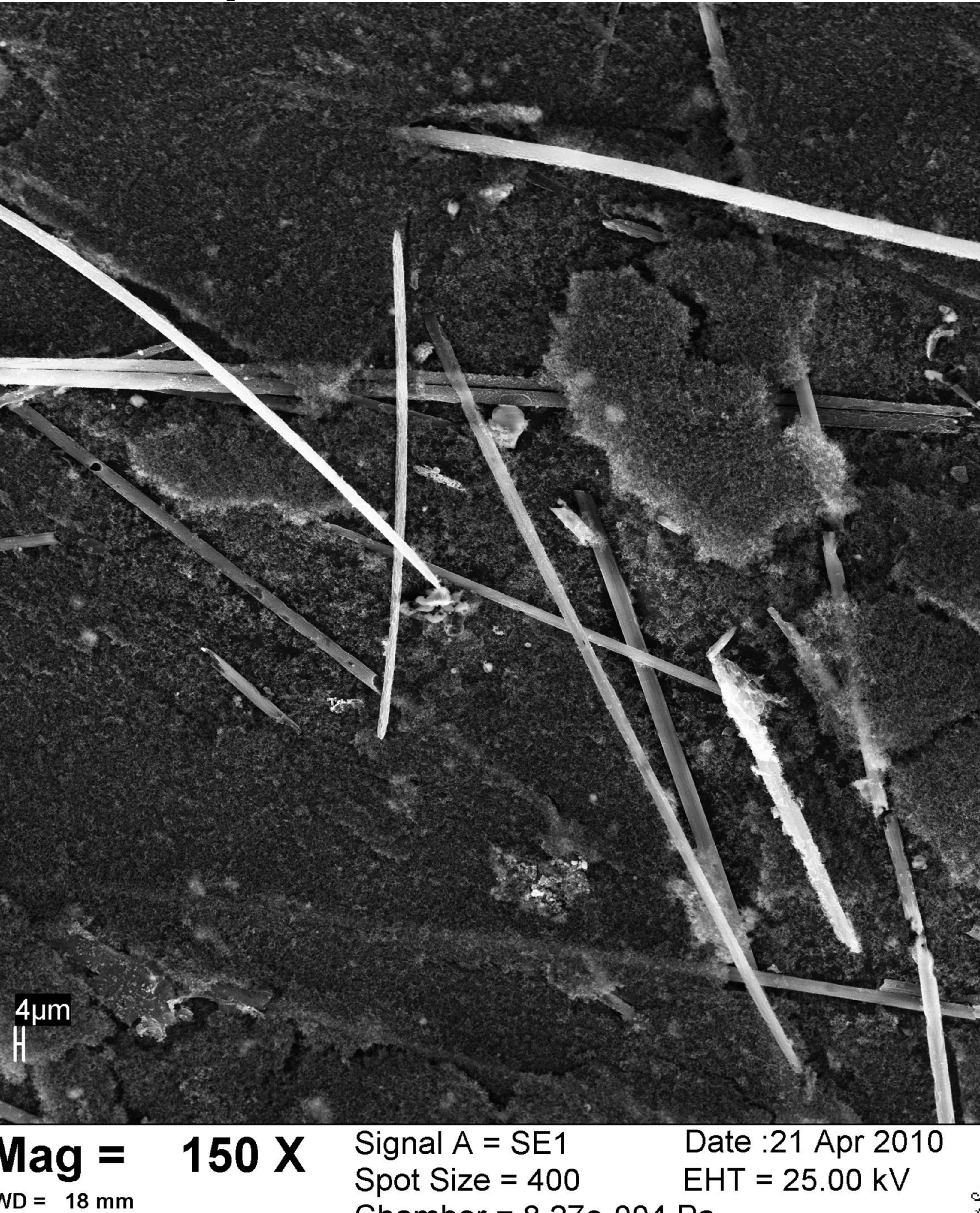
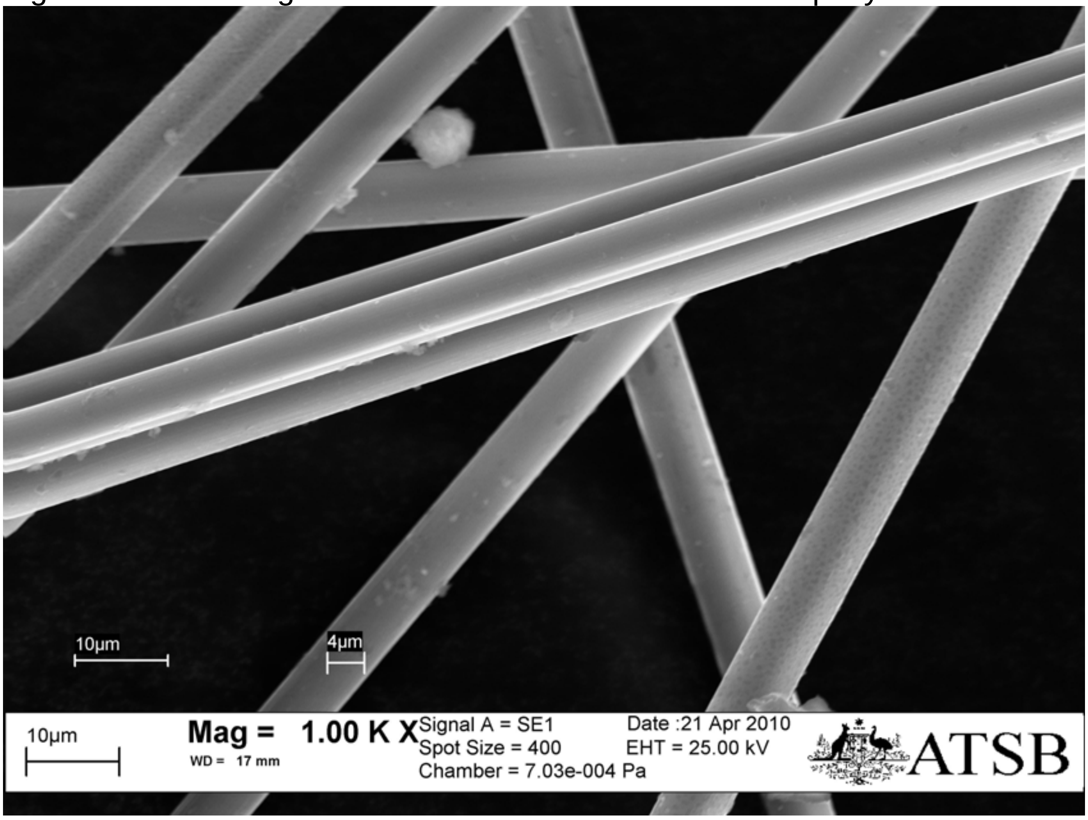


Figure 15: Undamaged carbon fibres liberated from the Epoxy substrate



Author's note

Further Research

This experiment was very much preliminary research and its primary purpose was to justify whether, and what, further research should be performed, however the findings of this experiment are significant enough to justify some very comprehensive follow up research.

The first thing that should be studied is the actual risk presented by the various fibre's produced, because this reports assumptions of how dangerous the carbon fibres are, are only based off informed estimations.

If follow-up's to this experiment continue to imply that there is a noteworthy danger presented by these particles, then comprehensive testing will need to be performed, looking across the range of these variables:

- The voltage and amplitude of the electricity ranging from AC power within a house to lightning.
- The period of time that the carbon fibre is eroded.
- The amount of energy as compared to the amount of carbon fibre being eroded.
- Variations on the carbon fibre:
  - Other substrate's apart from epoxy.
  - Electricity being run across the grain of the carbon fibre as opposed to with it.
  - Carbon fibre which has the fibres set differently, for example short fibres which point in different directions, so that the electricity can not pass all the way through along a single fibre.
  - Carbon fibre with protective metal mesh like that used to protect aeroplanes.

The Odds and Risks

The reason research like this is done is to answer a simple global question, "what is it, and will it kill me?", this research can't give you a conclusive answer to that question however I can give you an educated opinion on the best and worst plausible scenario's.

How dangerous is it, really?

The best case scenario would simply be that because carbon fibre is a dense material it may sink and settle out of the air fairly rapidly, almost completely avoiding the inhalation altogether. In addition, the inhaled fibres would be so much stronger than asbestos that they didn't splinter further after being inhaled, making them less dangerous. This strength would mean that after inhalation they would become rapidly lodged in the lung and not fragment, meaning that they could not float around doing any more damage.

The worst case scenario is that the fibres are critically structurally compromised and will continue to split off into smaller fibres. This is similar to the way that they themselves split off from the parent fibre. Carbon fibres are much sharper, more rigid and strong than asbestos and they can actually cause far more physical damage to a human lung than even the most dangerous forms of asbestos.

Both these scenario's are plausible, but most likely the fibres are marginally less dangerous than estimated in the paper.

The two most worrying things which might potentially produce a similar reaction from carbon fibre are; AC power of the variety found along power lines and in houses, and lightning, (to clarify, most worrying in this case means not that they are the most likely to produce this result, but that if they produced this result then it would cause the largest problem). The damage that fibres of this ilk do is chronic, not acute, so short term exposure is not such a problem, outcomes such as permanent damage to the lungs and death only arise when there is regular and prolonged exposure, such as at home, at work or at school. These conditions of prolonged exposure make airborne carbon fibre of negligible risk to most people because any exposure they receive will be over an insignificant period of time, yet there are some people who are at significant risk.

An example of potential regular exposure is when a carbon fibre aeroplane is struck by lightning; the lightning is conducted away by a copper mesh that is destroyed in the process, causing only local damage to the carbon fibre around the mesh and the site of the strike. The aircraft maintains structural integrity and lands safely.

The potentially dangerous part is for the people whose job comprises of repairing the carbon fibre that has been lightning struck; they must first remove the damaged carbon fibre, agitating the loose fibres which potentially releases dangerous fibres into the hangar where the planes are repaired. The fibres in the hangar would be constantly replenished by new damaged planes, and the people who repair the carbon fibre would be in this building every day, breathing in the fibres. Even if only one in ten planes that came through released dangerous fibres, over time some serious damage could be done. Consider that both the amount of raw energy in the lightning and the quantity of the carbon fibre in the plane dwarf those used in this experiment; although the lightning lasts for a far shorter period of time than the welder did.

The other large concerns lie in wiring; if wiring is done properly and safely, then there is no real risk, but unfortunately, sometimes mistakes are made. If my fears are correct then modern constructions are becoming far more dangerous places to wire incorrectly. My concern is that under certain conditions, ordinary AC power may be able to produce similar results in carbon fibre to those of this experiment. For a sense of perspective, the amount of electricity used in this experiment that produced dangerous fibres in just 30 seconds, was not even half of what is wired into a moderately large house all the time. Today, carbon fibre is being used as a high strength building material, there are 3 types of structures which seem to be at the most potential risk: carbon fibre reinforced bridges, skyscrapers and houses that use carbon fibre beams as a light and strong substitute for wood or steel. Buildings like this are actually far more common than many people realise.

The first concern mainly applies to bridges and skyscrapers, both have high voltage cables running through them, to transport large amounts of electricity. There is a chance that over time, bad wiring could allow electricity to erode the fibres themselves, inside the epoxy, in a way similar to what is seen in the preliminary research. The wiring could undetectably cause the piece of structural carbon fibre to lose the strength and integrity provided by the carbon fibres, until it is put under heavy strain; when it simply breaks where it should have held easily.

The second concern relates mainly to houses and skyscrapers, where, in a truly asbestos like fashion, unnoticed, a piece of carbon fibre could be slowly but continuously eroded to release dangerous particles that would circulate through a building, helped along the way by air conditioning and heating systems.

This is the worst case scenario; fortunately it is also very unlikely; first and foremost, the carbon fibres are encased in epoxy which holds them in place. All the reactions to produce these fibres so far have involved rapid and high temperature combustion of the epoxy to remove it completely from the fibres, so the epoxy would have to burn, but not set anything else on fire, and even then remain unnoticed, which is unlikely. Also the currant in most spark generated plasma is proportionately significantly lower in voltage and higher in amperage than most conventional AC power.

These examples are relatively unlikely to come to pass, and are being considered not because of the chances that they might happen, but because of the catastrophic impact if they did happen: if AC power could have this effect then there would be a chance that bad wiring could shorten the lives of tens, maybe hundreds of thousands of people.