FSP of SWNT to Increase the Thermal Conductivity of Aluminum

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ABSTRACT

Objective

The objective of this research is to show that friction stir processed (FSP) single-walled carbon nanotubes (SWNT) into aluminum increases the thermal conductivity of aluminum.

Findings

SWNT were FSP into aluminum and then rolled to a 50% and an 80% reduction in area in order to potentially align the SWNT in the direction of rolling. Rolling the FSP SWNT appeared to have aligned the SWNT at least at a macro level. Preliminary thermal conductivity testing has shown a slight decrease in FSP SWNT into an aluminum substrate. Previous research has indicated that poor interfacial bonding has occurred in aluminum-CNT metal matrix composites. At this time, it is believed that the cracks formed during the cold rolling process plus the poor interfacial bonding resulted in a slightly decreased thermal conductivity. Hot rolling has been determined as a way to eliminate cracking and future work will focus on increasing the interfacial bonding between CNTs and aluminum.

INTRODUCTION

Background Information

Single walled carbon nanotubes (SWNT) have many remarkable properties. One of which is their excellent thermal conductivity values reaching 6000 W/m-K [5]. By comparison, pure aluminum has a thermal conductivity of ~ 220 W/m-K. Although SWNT are very thermally conductive, scaling them up from the nano level to large scale applications has proven to be difficult.

Friction stir processing (FSP) is a solid-state process where a rapidly rotating pin tool is plunged into the surface of a metal, then traversed across the surface in order to be processed. The heat created by the friction between the metal and the pin tool is enough to soften and plastically deform the metal enough to force the metal to stir with the rotating pin tool. Traditional applications for FSP are used to locally eliminate casting defects, refine microstructures, and dispersing reinforcing particles [10].

Previous Research Review

Previous research has already concluded that nanotubes can withstand the temperatures and stresses involved in friction stir processing (FSP) with aluminum and magnesium substrates [7, 9, 12]. The scope of research in FSP of CNT is very limited, but significant increases in hardness of AZ31 and Al 7075 substrates were observed in the nugget region of the FSP CNT [7, 9]. No known research to date has explored increases in thermal conductivity of any substrate with FSP CNT or aluminum-CNT metal matrix composites [1-3], which have been reported to have poor interfacial bonding between the aluminum and the CNTs [2,8].

Objective

The objective of this research is to show that FSP SWNT into aluminum increases the thermal conductivity of aluminum.

BROADER IMPACT

According to Moore's Law, the processing speed and memory capacity of integrated circuits doubles about every two years. This is because the number of transistors that are able to inexpensively fit onto an integrated circuit doubles every two years as well. This trend has continued since the integrated circuit was invented in 1958 [11].

One of the problems arising in small electronics is cooling the circuit boards. Moore's law also applies to the heat generated by circuit boards which is doubling accordingly with the processing speed. As the circuit boards are shrinking, less and less room is available for heat dissipation. In order to remove heat on ever shrinking circuit boards with ever rising heat generation, new and creative ways will be needed to keep circuit boards from overheating [11]. The most popular methods of dissipating heat especially in small electronics are heat sinks and fans. Heat sinks require more mass and more volume to dissipate more heat and fans are a battery drain on small electronics.

This is one of many possible applications of a super thermally conductive aluminum-CNT composite. If this research is successful, designs of small electronics may be able to partially if not fully eliminate heat sinks and fans by building the frames of electronics out of this super thermally conductive aluminum-CNT composite. This would in turn allow for even smaller, faster, lighter, and lower energy consuming electronics.

PROCEDURE

Materials

- Single-walled carbon nanotubes 2 nm x 20 µm (Beijing Beida Green High Technology Co Ltd.
- 1/8" x 6" x 12" Al 1100-O Sheets
- Pure Aluminum Powder (Supersonic Spray Technologies)
- 1/8" Al 3003 square tubing (K & S Engineering)

Prewelding

The 1/8” aluminum tubes were packed with 100% aluminum powder and 100% single-walled carbon nanotubes in an argon chamber (Figure 1). This was done because it has been discovered that carbon nanotubes will begin burning in atmosphere at 400°C and be completely burned by 600°C. In an inert environment, nanotubes will withstand temperatures as high as 1000°C [4]. Temperatures of ~500°C are typical in FSP aluminum [10].

Figure 1. – Aluminum powder and nanotube packing process.

The aluminum tubes were sandwiched between two Al 1100 plates with 1/8” wide machined grooves as shown in Figure 2 and Figure 3.

Figure 2. – Aluminum tubes packed with aluminum powder and carbon nanotubes between two aluminum plates.

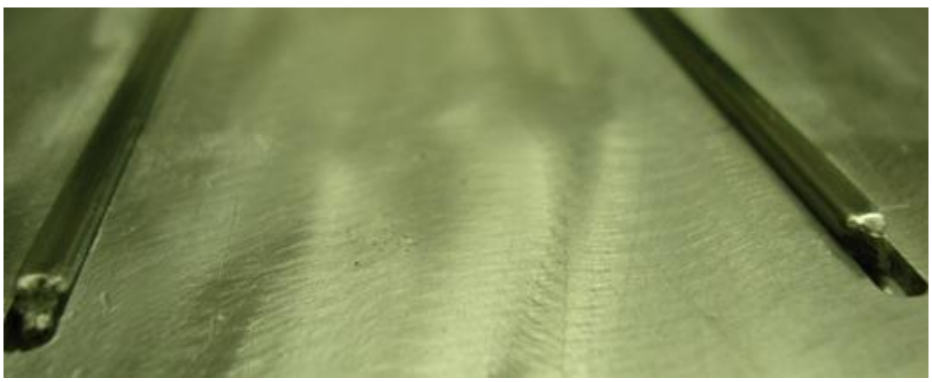


Figure 3. – Aluminum tubes sitting in machined grooves.

Welding

Each tube was FSP with a Ferro-Tic fixed tapered spiral tool shown in Figure 3.

Figure 4. – Ferro-Tic fixed tapered spiral tool.

Three passes were made by the tool on each tube (Table 1). The first was right down the centerline and the second and third passes were offset 0.1” on either side of the first pass (Figure 5). The pin at the base is 0.2” and the offset distance was chosen to be half of the pin’s diameter to promote better dispersion of the SWNT into the aluminum.

Figure 5. – Overlapping FSP of SWNT.

Table 1. – FSP 11-16 and their parameters.

Weld #	Tubing Content	RPM	IPM	Forge Force (lbs)	Heel Plunge	Lead Angle (^{o})	Weld Length (in)
11	Pure Al	1400	6	825-800	-0.003”	3.5	10.5
12	Pure Al	1400	6	800	-0.003”	3.5	10.5
13	Pure Al	1400	6	800	-0.003”	3.5	10.5
14	SWNT	1400	6	800	-0.003”	3.5	10.5
15	SWNT	1400	6	800	-0.003”	3.5	10.5
16	SWNT	1400	6	825	-0.003”	3.5	10.5

Rolling

The FSP SWNT and pure Al powder plate (Figure 6) was placed in the Fenn Rolling Mill (Figure 7) and cold rolled down to .160", or a 36% reduction in area. Increments in the rolling process varied from .005" to .010"

Figure 6. – Welds 11-13 are Al powder and welds 14-16 are SWNT.

Figure 7. – Fenn Rolling Mill

Severe cracking was observed in the rolled SWNT sample (Figures 8,10). After the 36% reduction in area, both the SWNT and Al powder samples were annealed at 350°C for 20 min. and hot rolled down to 1/8" or a 50% reduction in area and .050" or an 80% reduction in area to help close up the cracks that propagated throughout the SWNT sample.

Figure 8. Cracks formed on bottom of the rolled SWNT sample after a 50% reduction.

RESULTS

Metallography

Macrographs

Cross and longitudinal sections were taken of the SWNT sample at 0%, 50%, and 80% reductions in area (Figures 9-11).

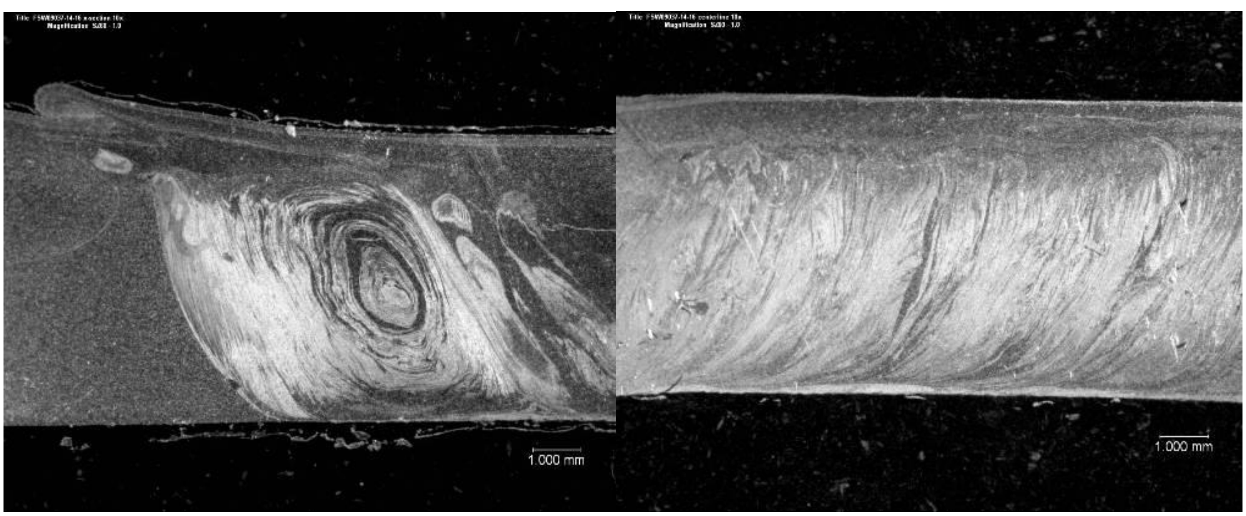


Figure 9. – Cross and longitudinal sections of SWNT specimen after FSP

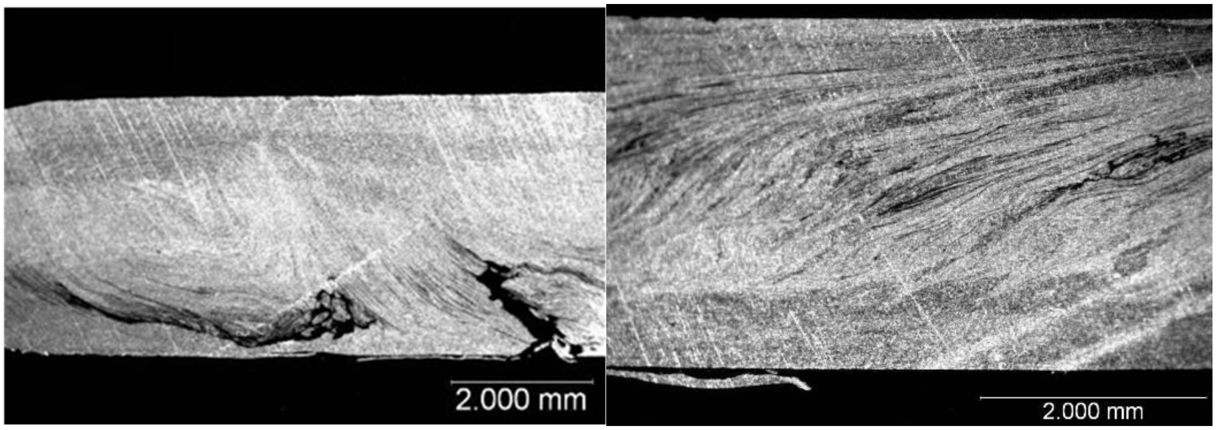


Figure 10. – Cross and longitudinal sections after a 50% reduction in area.

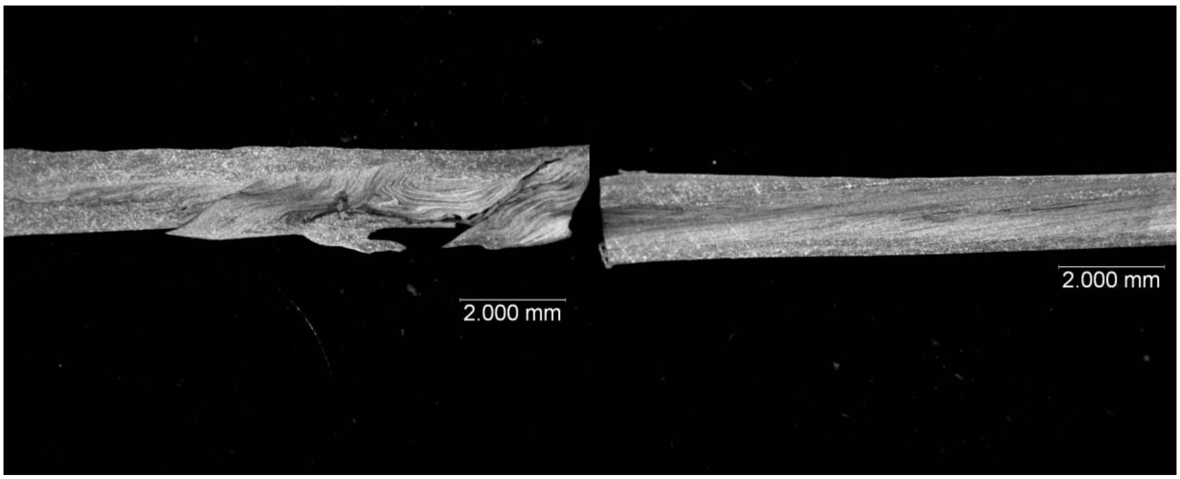
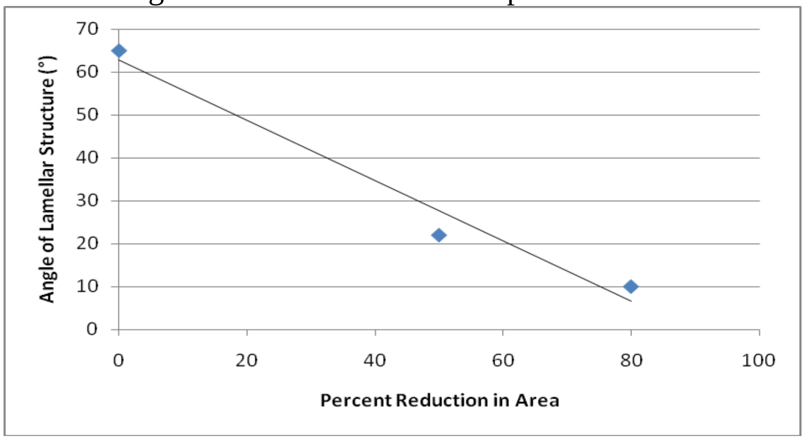


Figure 11. – Cross and longitudinal sections after an 80% reduction in area.

The average angle of the longitudinal lamellar structure appeared to decrease in a relatively linear fashion with increasing reductions in area (Table 2). The rolling appears to be successful in aligning the SWNT with the direction of rolling at a macro scale. Whether or not the SWNT are aligning at a nano level is not known.

Table 2. – Angle of lamellar structure vs. percent reduction in area.



SEM Analysis

The 1/8" FSP SWNT sample was fractured and observed in a SEM (Zeiss Supra 40 VP field emission). Intact SWNT were observed in the nugget region (Figure 12).

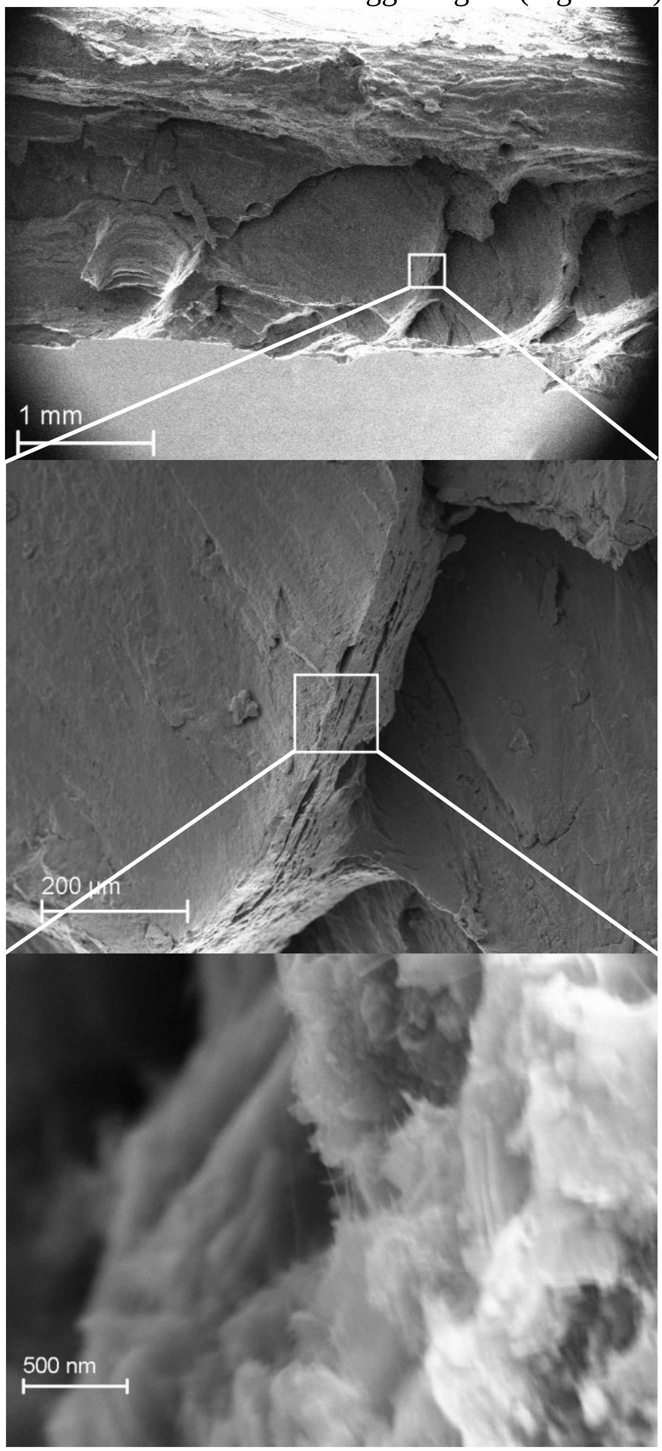


Figure 12. - Top: SEM of fractured SWNT sample with 50% reduction in area. Middle: Region occupied by SWNT. Bottom: Surviving SWNT located within the nugget region.

Thermal Testing

Thermocouples were attached to the 18" x 1" x 1/8" samples at 6", 12", and 18" from one end and dipped simultaneously into ~ 1" of liquid nitrogen (Figure 13).

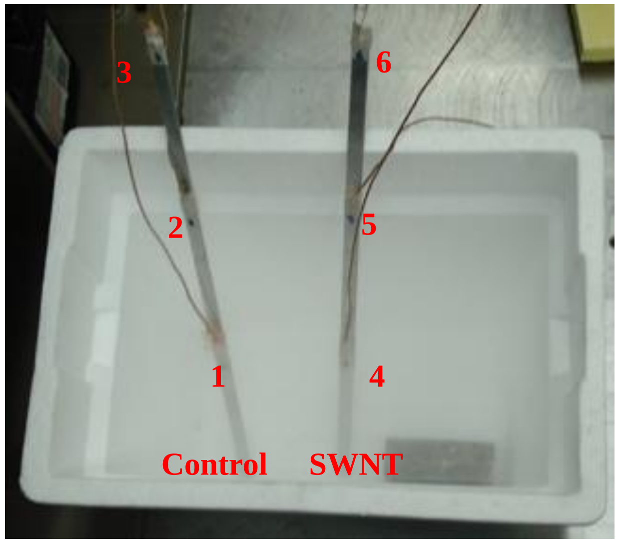
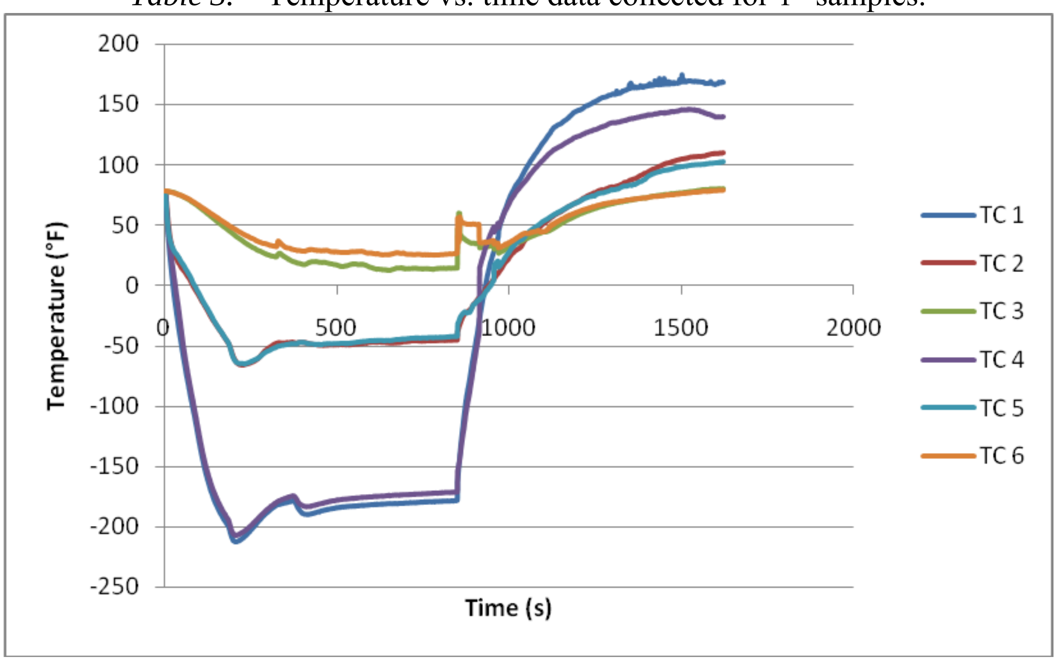


Figure 13. – Experiment setup. The control sample has thermocouple #'s 1,2,3 and #'s 4,5,6 are attached to the SWNT sample.

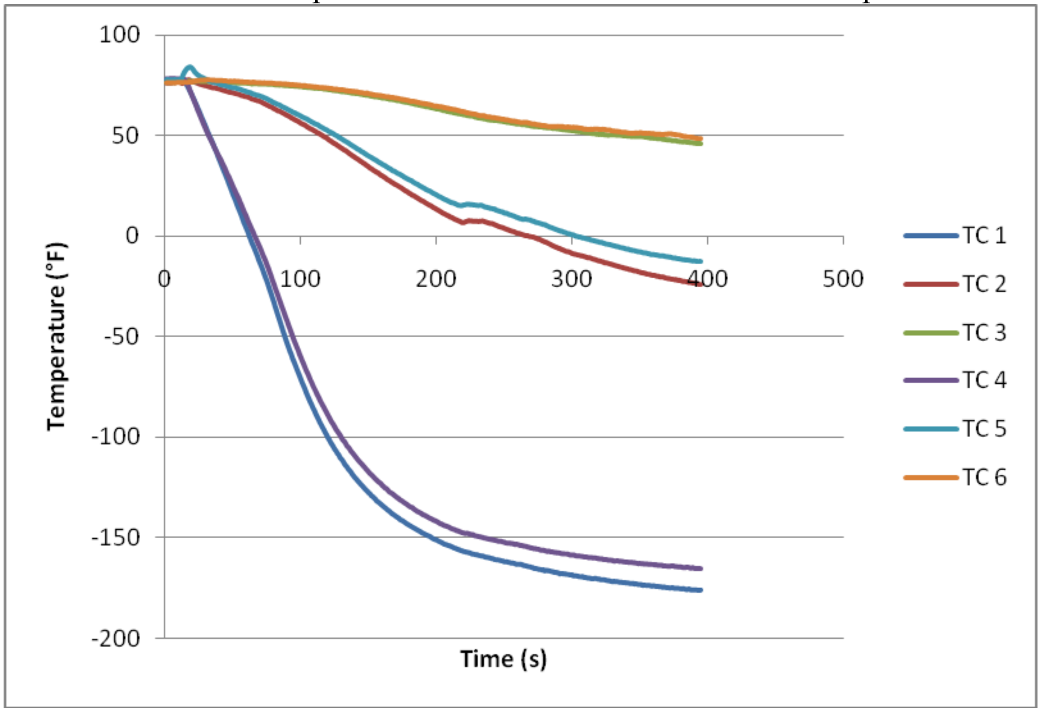
Once the temperatures on all thermocouples appeared to plateau, the samples were taken out of the liquid nitrogen and the ends were placed onto a hotplate. Temperature vs. time data was collected by thermocouples during the experiment (Table 3).

Table 3. – Temperature vs. time data collected for 1" samples.



The SWNT sample appeared to be slightly less thermally conductive than the control sample. To double-check, the samples were sheared down from 1” to ½” wide to isolate the nanotubes stirred within the nugget. The liquid nitrogen portion of the experiment was repeated and the temperature vs. time data was collected (Table 4).

Table 4. – Temperature vs. time data collected for ½” samples.



No significant difference was seen between the two tests, but when the SWNT sample was sheared down to 1/2”, voids on the edge of the nugget were present (Figure 14).

Figure 14. – Voids on the edge of the nugget post shearing.

Hot plate thermal testing was planned for .050” x ½” x 1-½” SWNT samples, but it was discovered that the samples were too thin and only erroneous values were returned during the testing procedure.

DISCUSSION

The rolling procedure appears to be successful in aligning the SWNT in the rolling direction at least at a macro level. Whether the SWNT are aligning at the nano level is unknown. A procedure to observe whether or not the SWNT are aligning has not been determined, but is an interesting factor that needs further exploration.

During the rolling process, the FSP SWNT sample began to crack significantly at the surface (Figures 8, 10, 14). The cracking indicates a rise in hardness as observed by Morisada et al. [9, 12].

Thermal conductivity of the 1/8" SWNT sample appeared to be slightly less compared to the control sample. Two known factors may have played a part in this result.

- Significant cracking during rolling created large interfaces throughout the sample that would slow the heat transfer in the sample.
- Poor interfacial bonding between CNT and aluminum in metal matrix composites has been reported [2, 8] which would also significantly slow heat transfer.

CONCLUSION

Summary

- SWNT have been FSP into aluminum without complete deterioration from the temperatures and stresses associated with FSP.
- Rolling FSP SWNT even in some of the softest of aluminum alloys requires frequent annealing and subsequent hot rolling of the samples to prevent severe cracking in the specimen. Annealing and subsequent hot rolling appear to align the SWNT very well on a macro scale, but the amount SWNT alignment at the nano scale is unknown and a procedure for determining alignment at the nano scale has not been determined.
- No increase in thermal conductivity in FSP SWNT has been observed. The known factors for this result are surface cracking during cold rolling and poor interfacial bonding between CNTs and aluminum in metal matrix composites.

Future Work

- Finding a way to measure thermal conductivity quantitatively. The comparison of the experimental samples with a control is the only current method of finding thermal conductivity
- Finding thermal conductivity of a SWNT sample encapsulated by FSW instead of FSP.
- Repeating the procedure for nanocopper and nanosilver powders, diamond particles, multi-walled nanotubes and electroplated nanotubes.

Future work of particular interest is a repeated procedure for FSP diamond particles and electroless copper plated SWNT. Aluminum-diamond particle metal matrix composites have been reported to have thermal conductivities as high as 580 W/m-K with a 0.9 volume percent diamond [6]. Electroless copper plated SWNT are of interest because the copper plating is expected to have a better bond with the SWNT than the aluminum substrate. Copper also diffusion bonds very well with aluminum which will hopefully eliminate the interfacial bonding problems seen in metal matrix composites. Better bonding should result in high thermal conductivities and possibly higher strength composites than previously observed.

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