Frictional Heating of Avalanching

Snow and the Sintering of Avalanche Debris

D.A. Miller*, E.E. Adams**, D.S. Schmidt**, and R.L. Brown**
*US Air Force Academy, Colorado
**Montana State University, Bozeman, Montana

Abstract: At the Montana State University Avalanche Research Site, instrumentation has been installed to measure temperatures, flow depth, and velocities during an avalanche. A small shed protects the personnel and data acquisition equipment from the avalanche flow. Five thermocouples have been installed along a 30 meter section of the avalanche running surface. Temperatures along the base of the flow were collected during several avalanches to observe frictional heating. The flowing snow did show a temperature increase as it progressed down the slope, but did not always approach the melt temperature. Snow samples were collected before the tests in the release zone and after the avalanches in the debris. The samples were preserved in the field with isooctane and then transported to the laboratory for examination. A computed tomography (CT) x-ray scanner was used to obtain images of the microstructural details of the pretest and debris snow samples. The CT images showed an increase in grain-bond coordination number when the pretest samples were compared to the debris samples. Using the microstructural parameters from the CT images, the growth of the new bonds in the debris was analyzed using a vapor diffusion sintering model. New bonds were shown to grow rapidly at the expense of small high-energy structures that resulted from the avalanche. The analysis showed vapor movement and sintering of new bonds due to surface curvature differences may be the primary debris bonding mechanism in snow that does not approach melt temperatures during an avalanche.

Keywords: snow and ice, snow crystal, snow crystal growth, snow crystal structure, snow metamorphism, avalanche debris

1. Introduction

One of the primary dangers associated with avalanches is the burial of victims in avalanche debris. Avalanche deposits become very strong and hard in a short period of time, necessitating the use of metallic probes and strong shovels to retrieve a burial victim. It has been reported that this rapid set or strengthening of avalanche debris is the result of frictional heating during the event. McClung and Schaerer (1993) describe a thin liquid layer on the grain surface that develops from frictional heating during the avalanche, although direct evidence is not presented. Once the debris halts, this small liquid layer rapidly freezes creating nearly instantaneous bonds. Of course, the amount of frictional heating is dependent upon the size and duration of the avalanche. In large avalanches, debris fields have been observed to be nearly isothermal at 0°C, making the melt-freeze scenario likely (Tremper, 2001). But in smaller avalanches (much more common), is there enough energy to consistently raise the temperature to melting? Also, after grains and clusters violently interact, what affect does the sintering process have on debris hardening? An avalanche debris experiment was designed to examine these questions and to provide an application for the metamorphism model described in Miller et al (2002).

Corresponding author address: D. A. Miller, Department of Astronautics, US Air Force Academy, CO 80840; tel 719-333-4088; email dan.miller@usafa.af.mil

2. Methodology

During the 00-01 and 01-02 seasons, debris was collected from avalanche experiments conducted at the Montana State University Avalanche Research Site located in the Bridger Range, MT. The objective was to collect and preserve avalanche debris at various time intervals starting immediately after an avalanche. In order to evaluate the significance of frictional heating, two sets of temperature measurements were desired. Snow temperatures in the flowing avalanche, as well as avalanche debris temperatures, helped determine what was happening during and after an avalanche. Temperature and temperature changes in the flow gave an indication to the amount of frictional heating during the avalanche while debris temperatures measured the snow's thermal state when it came to rest. Snow samples were collected before and after the avalanche for laboratory microstructural evaluation.

At the Revolving Door avalanche path in the Bridger Range, MSU has an avalanche research site consisting of a small shed and infrastructure to make various measurements during an avalanche. Five T-type thermocouples, spaced at approximately 7m intervals, were placed along the avalanche running surface to measure macroscopic temperatures of the flowing snow. To capture avalanche debris, a pit measuring approximately 1.5m long x 1.0m wide was placed in the avalanche path. As the avalanche passed by, the pit filled completely with avalanche debris. Snow temperature was monitored with thermocouples in the debris pit during the study period. The debris was then sampled and preserved within 10 minutes after the test. Samples were collected in 30 ml Nalgene containers, preserved with isooctane, and transported to the lab in dry ice. Once in the cold laboratory, binary images were created from CT scanner images. The images were then analyzed using Edens and Brown's (1994) stereology software. The samples were evaluated using a new metamorphism model (Miller et al, 2002) to quantify the affects of sintering in avalanche debris.

3. Results

3.1 Field

Three avalanche tests were conducted during the 00-01 winter season. Drought conditions in southwest Montana precluded a larger number of experiments. Table 1 gives the pre-test and avalanche debris snow densities as well as the average temperature of the debris immediately following the avalanche. Pre-test samples were collected in the avalanche release zone prior to the test. Notice in table 1 that none of the debris temperatures approached the melting temperature. While this does not preclude surface melting, as this temperature measurement is macroscopic, it does show that the entire debris pile did not become isothermal at 0°C. In large avalanches with long run outs, excessive frictional heating could raise the snow temperature to the melting point. Since the snow in these tests did not approach the melting point, it seems unlikely that all of the observed debris strengthening can be attributed to the freezing of liquid water on the grain surfaces. This does not imply that fictional heating is of no consequence. In the 19 Feb 01 avalanche test, temperatures were recorded along the base of the avalanche flow at the 7m interval. Figure 1 shows the snow's increase in temperature (from an initial temperature) along the avalanche test track. Since the initial temperature measured on the track prior to the test was probably different than the initial temperature of the avalanching snow, the absolute increase in temperature of the flowing snow is unknown. In figure 1, the time-phased nature of the flow is evident as the temperature changes occur later for thermocouples further down the slope. It also appears that the temperature change tends to increase the farther the avalanche has run. Figure 2 shows the actual temperatures along the track. In general, as the avalanche progressed down the slope, the absolute temperature appeared to increase.

In figure 2, the temperature measured by the upper most thermocouple was consistently warmer than the others. It is believed that this resulted from the warmer snow at the sliding surface contacting the thermocouple prior to significant mixing with the upper snow layers. In order to confirm this theory, snow profile temperatures within the release zone were added during the 01-02 season. On 2 Mar 02, an avalanche test under relatively cold conditions was conducted. The avalanche released approximately 30 cm deep near the top of the running track. The 30cm pre-test temperature was measured at -7.1°C while the 10 cm layer was -10.1°C. Figure 3 shows the temperature data along the base of the flow. The temperature near the top (0 m) starts at the sliding layer initial temperature, but increases with time as the snow from higher on the slope flows over the thermocouple. At the next thermocouple (7 m), the snow has mixed, lowering the flow temperature (as measured at the base of the flow). After mixing, the temperature of the flow increases as it progresses down the slope, presumably from frictional heating.

Table 1. Density of pre and post avalanche snow with debris temperatures.

Date	Pre-test Density (kg/m^3)	Debris Density (kg/m^3)	Debris Temp (C)
19 Feb 01	260	450	-5.5
15 Mar 01	117	407	-4.6
31 Mar 01	230	420	-1.2

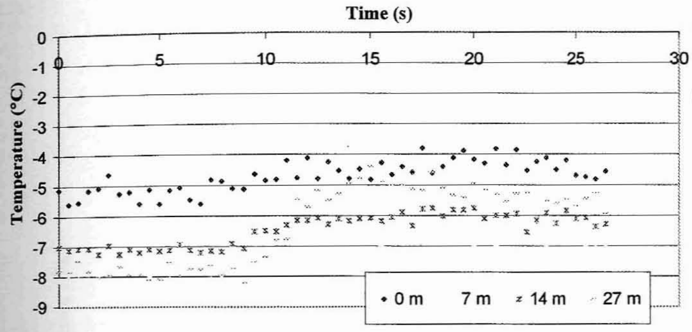

Figure 1. Temperatures at the base of the 19 Feb 01 avalanche flow.

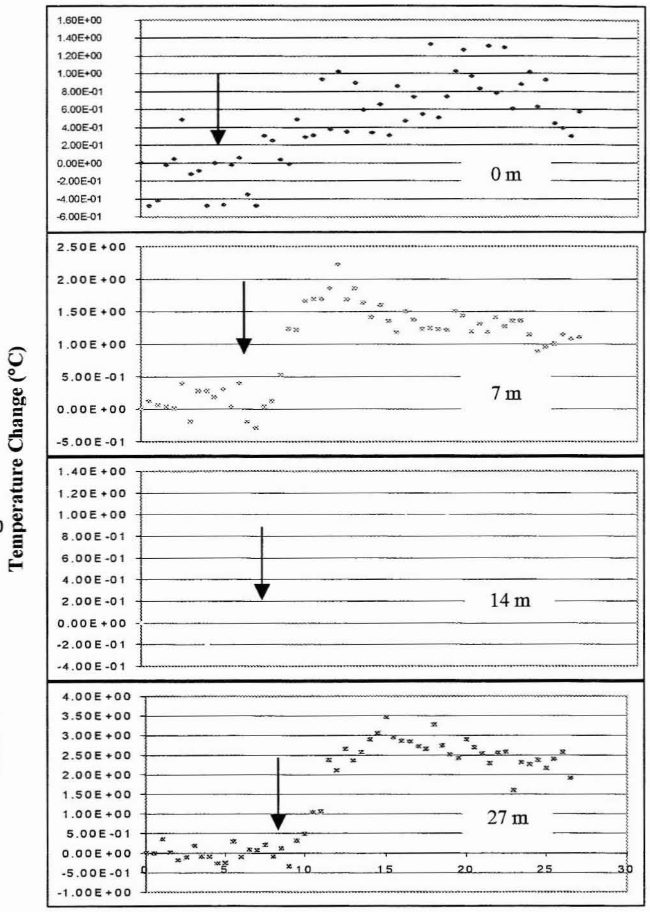

Figure 2. Temperature change at the base of the 19 Feb 01 avalanche flow. Distance from upper end of the test track is indicated. Arrows indicate arrival of the avalanche at each thermocouple.

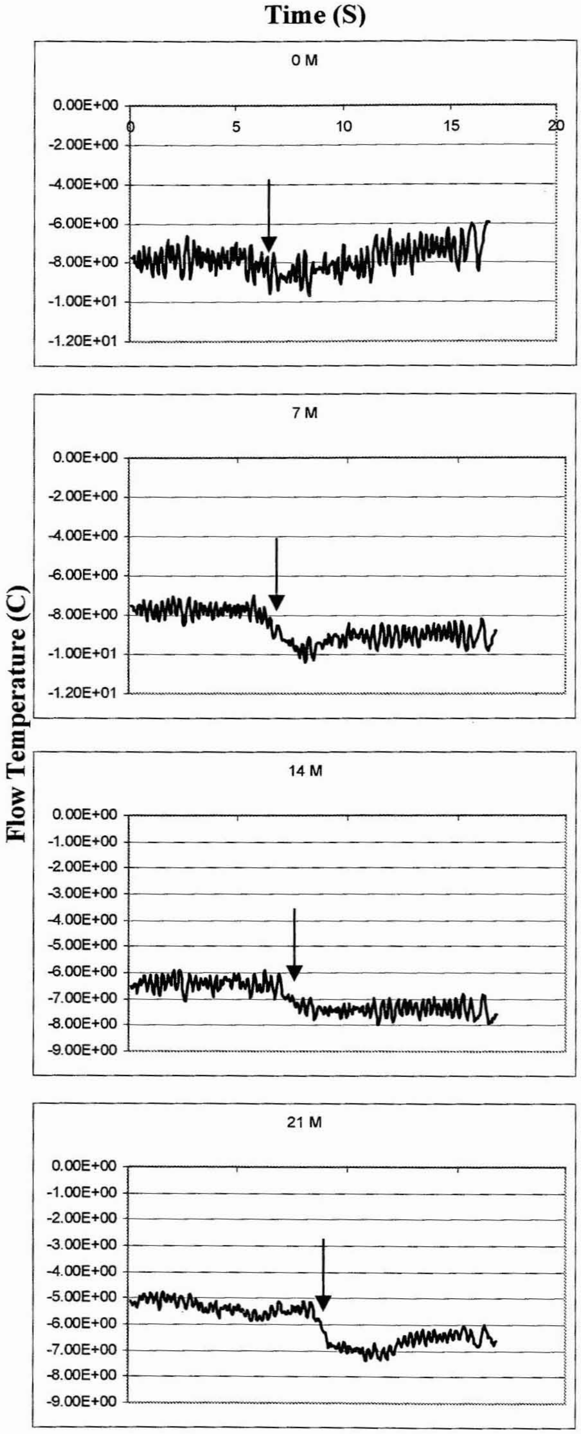

Figure 3. Temperatures at the base of the 2 Mar 02 avalanche. The arrival of the flow at each thermocouple is evident as an initial temperature decrease. Arrows indicate arrival of the avalanche at each thermocouple.

3.2 Laboratory and Numerical

After the preserved samples were transported to the laboratory, they were CT scanned and processed to obtain binary images of microstructural details (Miller, 2002). It was originally envisioned that the grain and bond data from the stereological evaluation of the binary images would be compared to the numerical evaluation of the sintering process. Accurate bond data was not obtained from the images primarily due to limitations of the CT scanner. Obtaining high contrast and resolution images of the high density debris samples filled with isooctane proved very challenging for the CT scanner. As a result, bond measurements were deemed unreliable as the details of these small features were the first features lost. On the other hand, the grain measurements appeared consistent and similar to field observations. Since grains are much larger than the bonds, they were less affected by noise and contrast issues. The CT imaging process resulting in binary images is described in Miller (2002).

The stereological analysis produced two-dimensional coordination numbers from the binary images. The coordination number is a measure of the average number of bonds per grain. The stereology package (Edens and Brown, 1994) measured the number of grains (as a percentage) for each coordination number. This parameter is particularly useful since the strength of the snow should increase as the number of bonds per grain increases. Even though the details of the bonds were not accurately captured due to their small size and dense samples, the number of connections between grains seemed reasonable. The density increases shown in table 1 should accompany an increase in the coordination numbers as the snow is consolidated during an avalanche. Figure 4 shows an overall increase in the number of bonds per grain from before and after the avalanche. As expected, the number of bonds increased significantly in the avalanche debris. Bond growth is examined next using the numerical metamorphism model.

With the increase in the number of bonds evident in avalanche debris, what is the growth rate of these bonds after an avalanche event? The new bonds were evaluated using Miller et al (2002) numerical sintering model. It was assumed that the bonds were broken during the avalanche and began to grow again in the debris pile. The modeled microstructure was defined by the CT grain size in the debris pile, initial bond to grain radii ratios of 1%, and density and temperature from the field recorded values. Sintering was allowed to progress with these parameters. As already discussed, the amount of intergranular bonding is a measure of snow strength. In figure 5, the increase in bond area is calculated for the first 30 minutes following the 19 Feb 01 avalanche. During the first 30 minutes, the calculated bond area within the avalanche debris increased over 200 times, significantly strengthening the debris. The rapid increase in bond area coupled with the increase in bonds per grain present an alternative to the melt freeze explanation for the hardening of avalanche debris. Considerable research potential still exists on avalanche debris, but the avalanche debris sintering problem provided an excellent application of the sintering model.

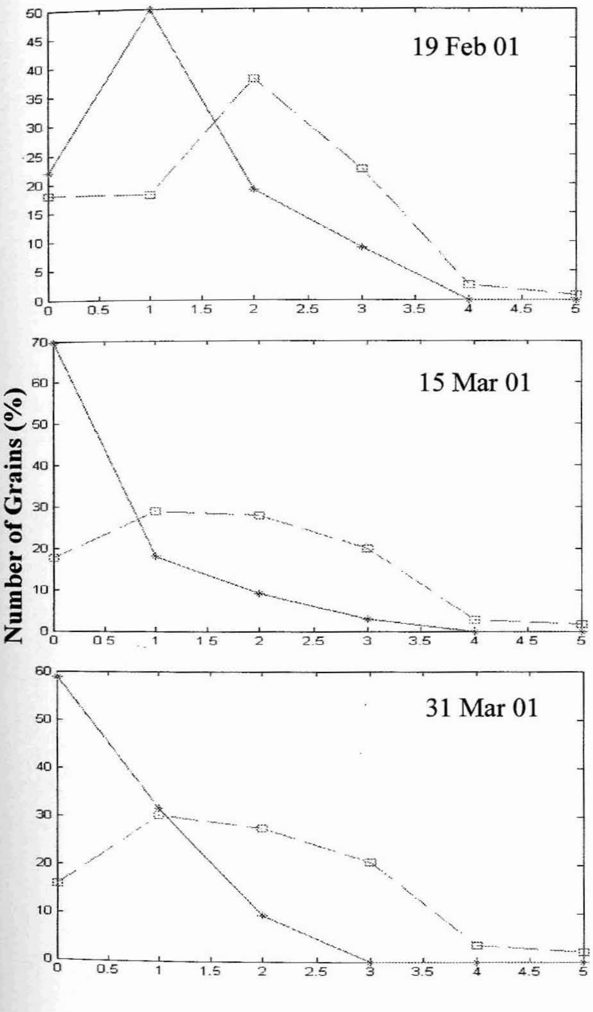

Figure 4. Two dimensional coordination numbers of pre and post avalanche snow from CT binary images. * - Pre-Test, □ – Avalanche Debris

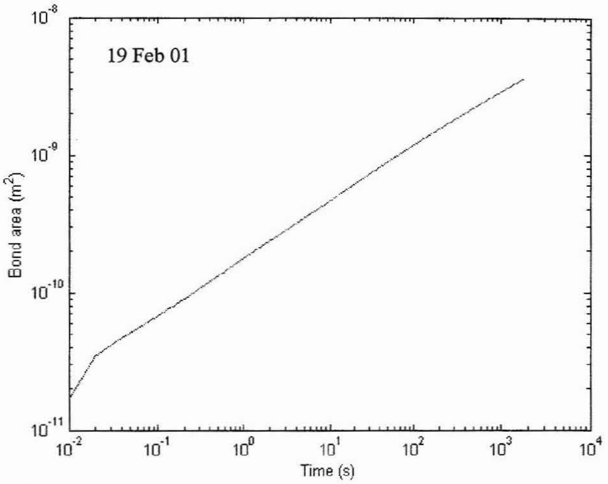

Figure 5. Bond area growth between grains as a function of time in avalanche debris.

4. Conclusions

This experiment and analysis examined the metamorphism of avalanche debris. Limited temperature data indicated that temperatures in small avalanches do not always approach the melting temperature. A sintering analysis using measured debris parameters found that rapid growth of bonds, in the absence of liquid water, may be a major contributor to the hardening of avalanche debris.

5. References

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