A Study of the Influence of Surface Roughness on Heat Transfer

A Major Qualifying Project Report:

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In Mechanical Engineering

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Abstract

A silicon based sand paper was used to polish the test materials. The surface textures of the aluminum samples were measured using an Olympus LEXT 3100 scanning laser microscope. Area-scale analysis was also used to determine at which scale the most heat transfer was observed.

Introduction

1.1 Objective

The experiment was conducted in order to test how surface roughness affects the rate temperature rises in aluminum.

1.2 Rationale

The effects of surface texture on heat transfer are not yet known.   The reason for this experiment is to provide initial observations on the effects that increasing surface textures have on the amount of heat transferred. Knowledge obtained in this experiment may further studies in surface metrology and may improve products that are used today and possibly in the future.

The U. S. department of Energy states one of the common designs for solar hot water heaters involves a plate used to absorb heat.   There is a potential for improved solar hot water heaters by furthering our understanding of the affects of surface texture on heat transfer. This research could lead to an inexpensive process that could increase efficiency in solar hot water heaters.

Flat-plate collector: Glazed flat-plate collectors are insulated, weatherproofed boxes that contain a dark absorber plate under one or more glass or plastic (polymer) covers. Unglazed flat-plate collectors—typically used for solar pool heating—have a dark absorber plate, made of metal or polymer, without a cover or enclosure.

1.3   State-of-the-art

There is little known about the affects of surface roughness on heat transfer. One well known effect that surface roughness has on heat transfer is emissivity. Emissivity is defined as the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. Thermal Fluid Sciences defines a blackbody as a perfect emitter and absorber of radiation; at a specified temperature and wavelength no surface can emit more energy than a blackbody.   Emissivity only affects radiant heat transfer. As explained in the textbook Thermal Fluid Sciences, "Properties of emissivity strongly depend on surface conditions… This uncertainty is largely due to the difficulty in characterizing and describing the surface conditions precisely." Unfortunately more is not known about the effects surface roughness has on heat transferred. Searches for technical journals and books were conducted through the internet using various websites. A list of websites and search terms used can be found in the appendices.

1.4   Approach

The experiment used an ASTM standard as a guide to obtain data. Modifications were made to the design to conform to a real world application for solar hot water heaters. This experiment also requires the use of LabView and a custom VI was programmed for this experiment.

Methods

1.5   Test Box

ASTM standard E-781 was used as a guide for the assembly of the test box. The test box is an aluminum pan that was painted black on the interior as specified by the standard. A cover for the box

was constructed from a sheet of Lexan and used to prevent the interior temperature from being

affected by outside sources other than the test lamp. To minimize the effects of convective heat

transfer on the test material, glass spacers were used to raise the test material off the test box. Glass

spacers were used for their low surface area and low heat transfer coefficient. A piece of aluminum foil

was used to shield the thermocouple and prevent potential false readings from direct exposure to the

test lamp.
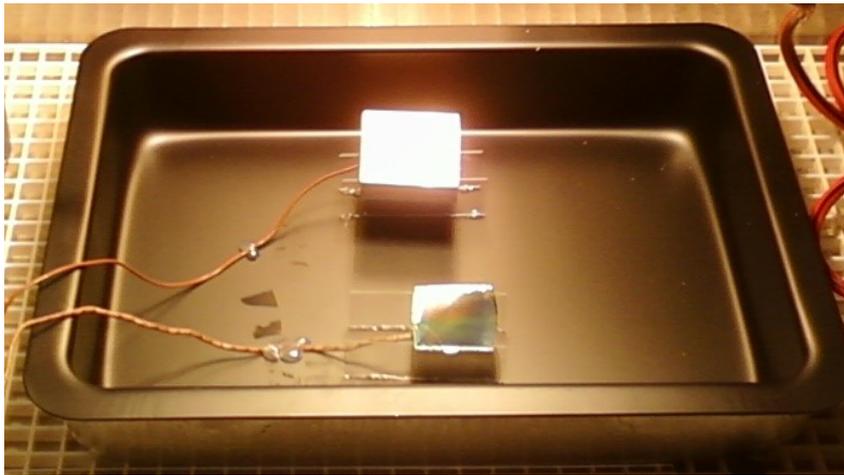
Picture 1: Test Box without cover

E 744 – 07

FIG. 2 Accelerated Exposure Absorber Mini-Box
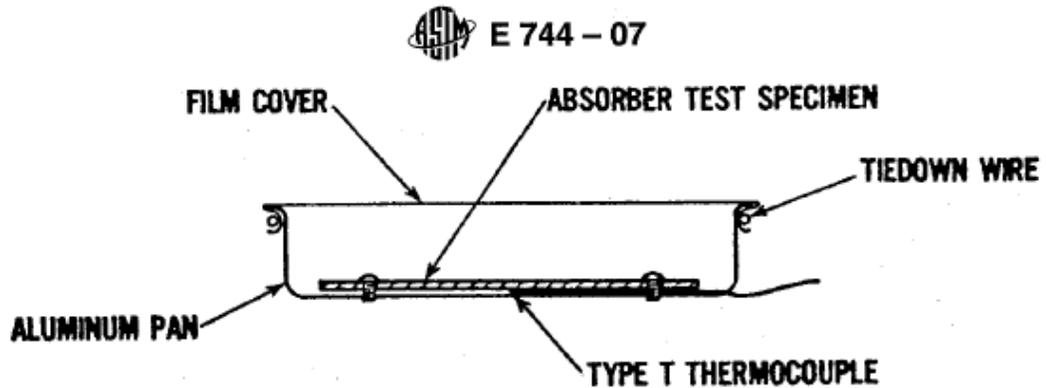
1—*Film Cover:* Polytetrafluoroethylene.
2—*Absorber Test Specimen:* 7.5 × 6.1 cm.
3—*Aluminum Pan:* 11.5 × 6.5 × 2 cm. Interior painted black and baked at 230°C for 24 h.

Figure 1: Test Box ASTM E-744

1.6   Test Apparatus

The test apparatus encompasses the test box, the test lamp, and the data acquisition device.

The test lamp used is a 300-600 watt halogen lamp. The ASTM standard calls for a Xenon Arc lamp.

Unfortunately a Xenon arc lamp is expensive and difficult to obtain. George Kelly from BP solar

suggested a Halogen work lamp, stating that the light produced is similar to that of natural light and the

lamp is considerably less expensive than a Xenon Arc lamp. Also, Halogen work lamps are easily

obtained at local hardware stores.

Picture 2: Test apparatus, Test box, DAQ, and Lamp

A data acquisition device (DAQ) was used to take temperature readings over time. The unit was developed by National Instruments and uses the program, LabView, also developed by National Instruments. A LabView VI was programmed to take temperature measurements of the box and the material simultaneously with respect to time. I went through many iterations of the program and performed many tests to insure that the VI would collect data consistently and accurately. After the programming the VI, I connected the DAQ to my computer and the test box.
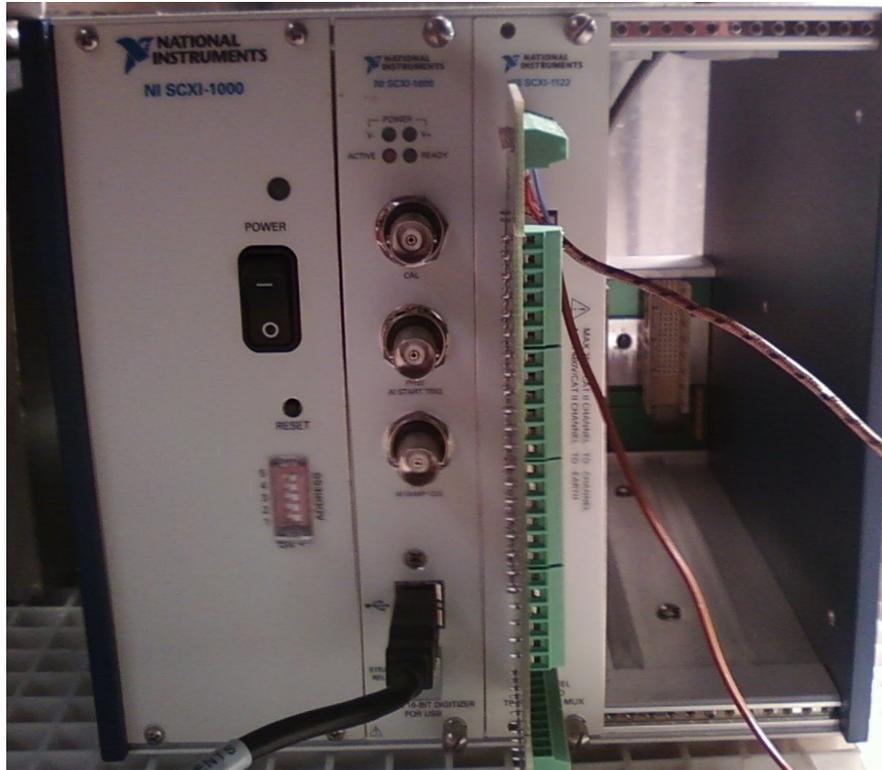
Picture 3: Data Acquisition device

1.7   Surface Texture Preparations

Four out of five aluminum test samples were prepared using Professor Li's suggestion of silicon based sand paper as suitable for the polishing process. One test sample was not polished to serve as a control. Sand paper with grits ranging from 240 (coarse) to 120, 400, and 600 (fine) were used. The unfinished test materials had large extrusion lines, created during manufacturing, which had to be polished down to provide a more uniform base. To remove the extrusion lines, the 240 grit (coarse) sand paper was used. After the extrusion lines were removed, I moved to a finer grit sand paper until the scratches produced by the previous polish were replaced with finer ones. This was repeated until

reaching the desired texture. It was also necessary to wash the test material with alcohol to remove dust and dirt from the surface prior to polishing

Surface roughness measurements were obtained using an Olympus LEXT OLS4000 Measuring Laser Confocal Microscope. The LEXT OLS4000 was an ideal machine to use for this experiment because of the use of lasers as well as user friendly software. The OLS4000 uses a 405nm laser to obtain high resolution measurements. Lasers are used in microscopy to decrease the wave length of a light source, allowing for higher resolutions. Each test material was cleaned before scanning with the microscope, to avoid false measurements.

After the measurements were made using the OLS4000, Area-scale analysis was used to display at what scale the test materials were affected the most by the roughened surface. The software SFRAX was used to perform area-scale analysis on the test samples.

1.8   Testing Using the Apparatus

The test apparatus was assembled in a dark room to mitigate the effects of foreign light sources. The test apparatus used thermocouples, wired into the box itself, for the temperature measurements, using my computer to store the collected data. A long cable allowed me to keep my computer outside the test room and avoid interference with the test. Each test ran for approximately 30 minutes, taking temperature readings about every 5 seconds. The test began as soon as the lamp was turned on. The box was allowed to cool for 30 minutes prior to testing each sample. Since the temperature of the room would fluctuate it was important to have a temperature reading at the start of each test to compare the differences in temperature.

1.9   Measure Temperature Using LabView

I programmed my VI to take 2 samples every 5 seconds: test material and box temperature. The

test would run for 30 minutes, the VI would record the test materials initial temperature and final

temperature as well as the test materials temperature every 5 seconds. The data was then sent to my

computer where I then converted it to Excel format. I chose to have readings every 5 seconds because

the temperature increase in the test material was not rapid.

Figure 2: LabView Block Diagram
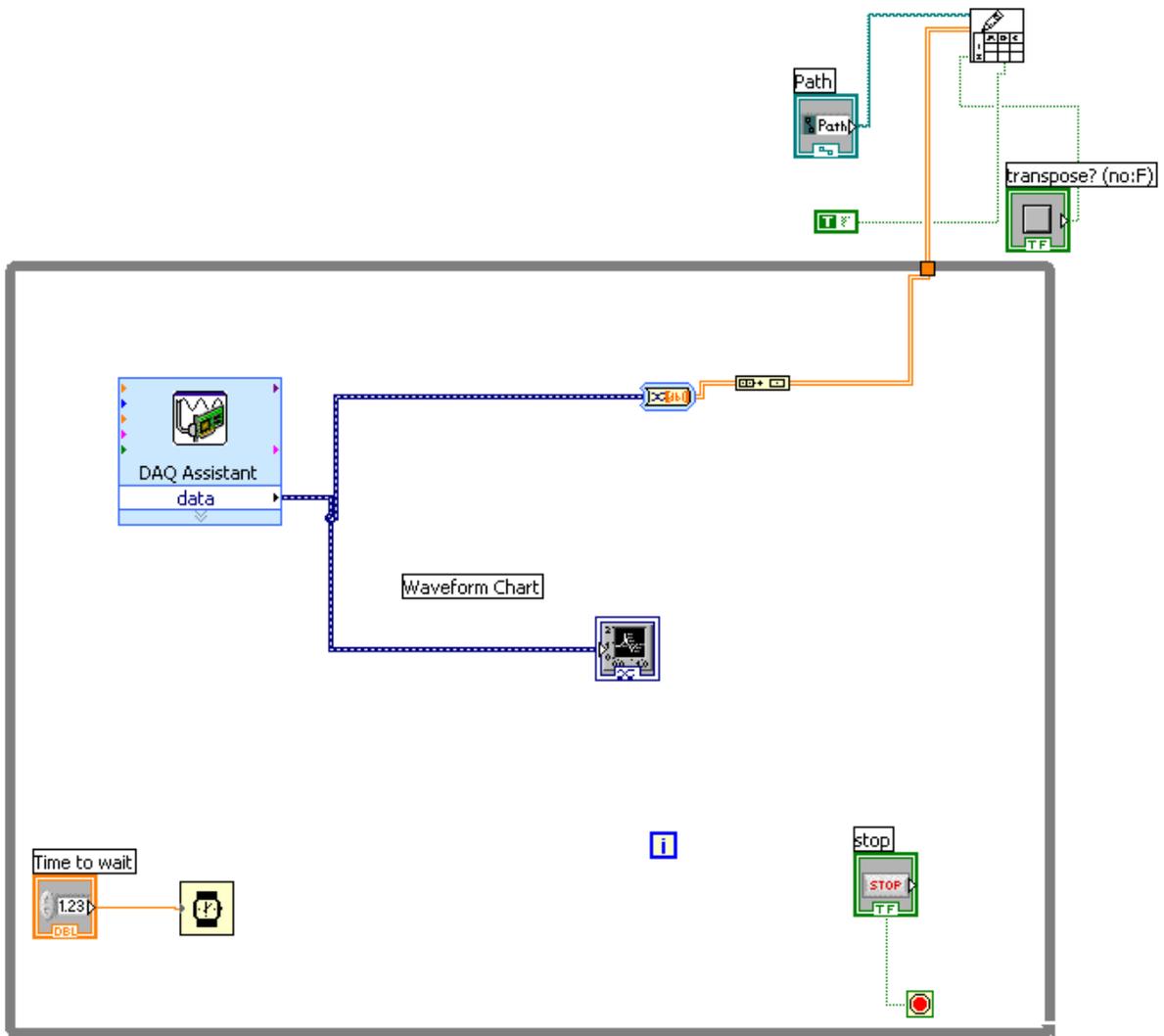
Results

1.10 Surface Processing

The surfaces of the test specimens were prepared using different grit sand papers and manually polishing the specimen to the desired state. Using the sand paper proved to be effective but time consuming. The process was also not uniform; it was difficult to produce the same texture throughout the test material. The inconsistent texture of the test materials affected the results of the experiment. Also, while polishing a test sample using grit of 600, I noticed a discoloration in the material. During polishing the test material became darker. This also affected my results due to more energy being absorbed by the darker material. The test material, SP600, polished with 600 grit, was considered an outlier. All test materials were weighed after polishing.

Picture 4: Test samples: Normal, SP120, SP240, SP400, SP600 respectively

1.11 Surface Measurements

Using the Olympus LEXT 4000 with the 50X objective lens to measure the surface roughness, data was recorded for all test specimens. The objective lens used was determined by measuring the roughness using 5X, 10X, 20X, and 50X lenses. After comparing the data from the measurements, I decided that the 50X lens provided the most precise and accurate readings. (A graph of the combined area-scale analysis is provided in the Appendix.) I then measured all test specimens with the 50X objective lens and compared the measured roughness. Figure 1 below shows the area-scale graph of all test specimens at 50X.
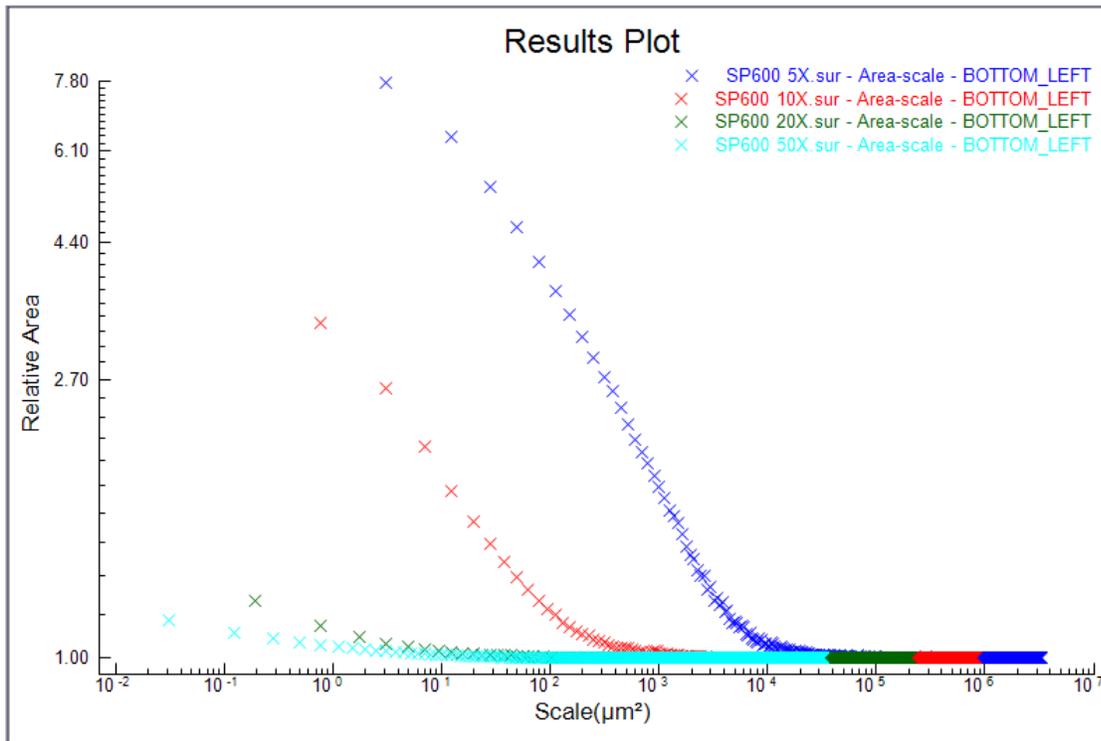
Figure 3: SP 600SFRX
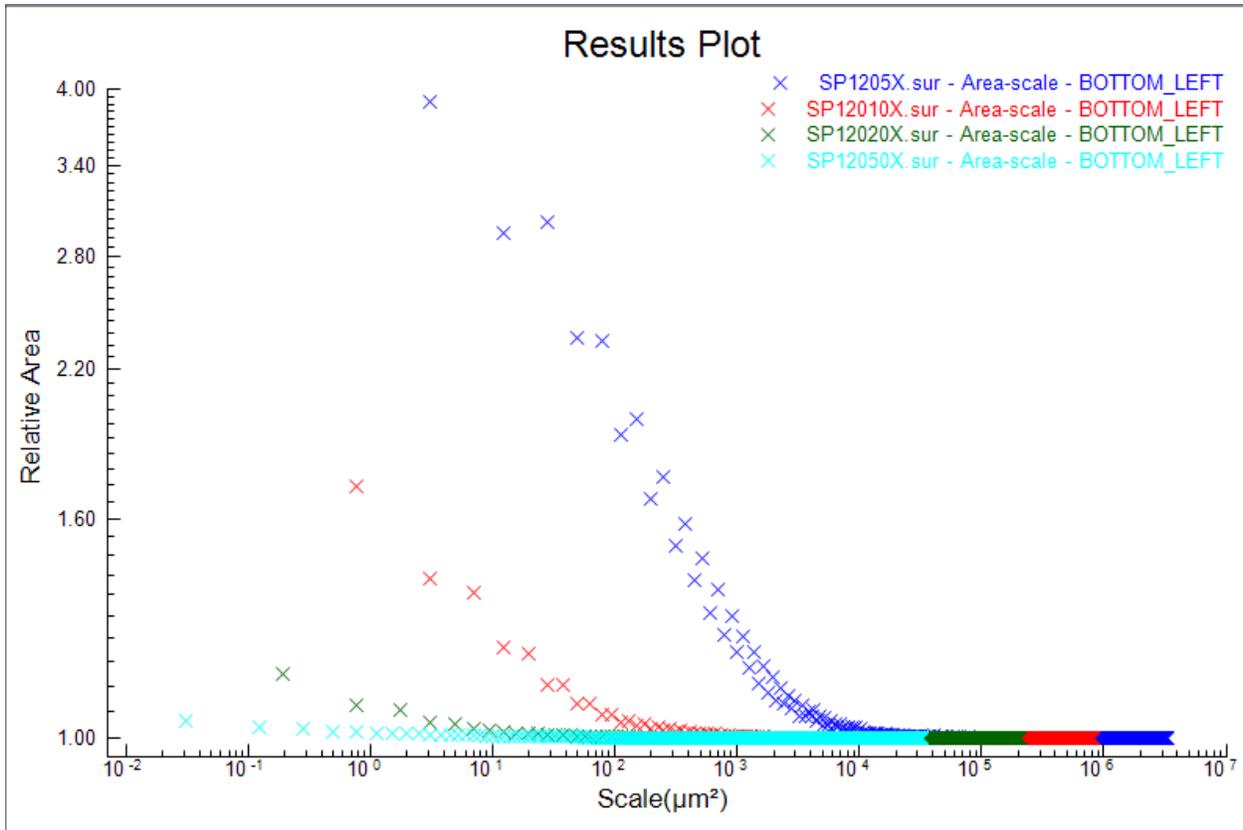
Figure 4: sp 120 SFRX

1.12 Temperature Test Results

Prior to testing, each test specimen was cleaned and its initial temperature was recorded. Figure

2 below displays temperature-time plots for all test specimens. Tables 1 and 2 display the final

temperature (Degrees Celsius) and the difference from initial and final temperatures respectively.

Table 1: Final Temperatures

Test

Sample	Final Temp. °c
Normal	45.104
SP120	43.272
SP240	41.158
SP400	43.037
SP600	51.009

Test

Sample	Difference in Temp °C
Normal	18.997
SP120	15.76
SP240	14.158
SP400	16.433
SP600	24.988

Table 2: Differences in final temperatures
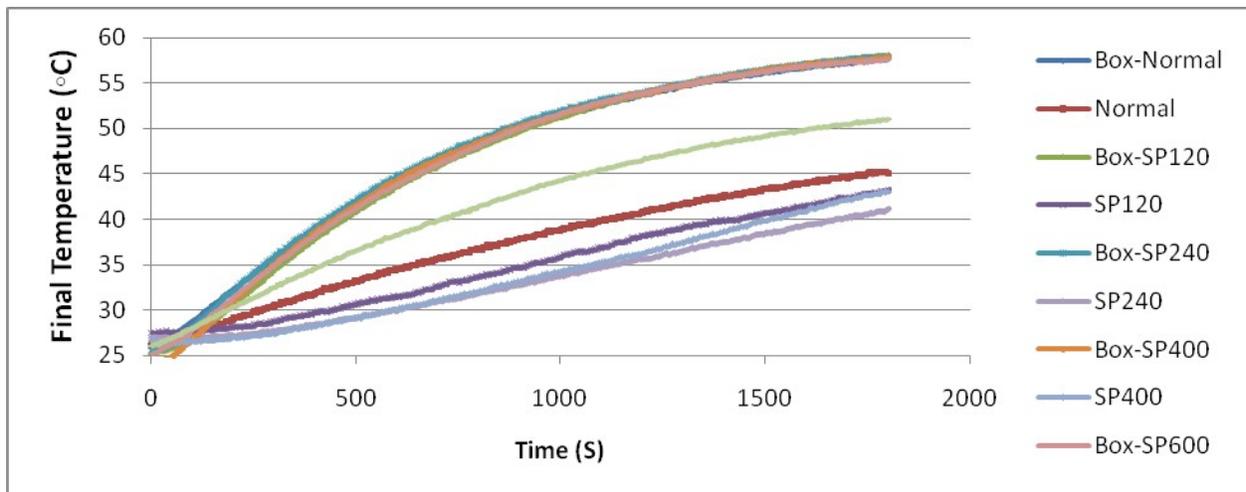
Figure 3: Temp-Time

Each test did not start at the same temperature.

Figure 3 above displays the raw test data, while figure 4 below displays the change in Temperature-time

plots for all test specimens
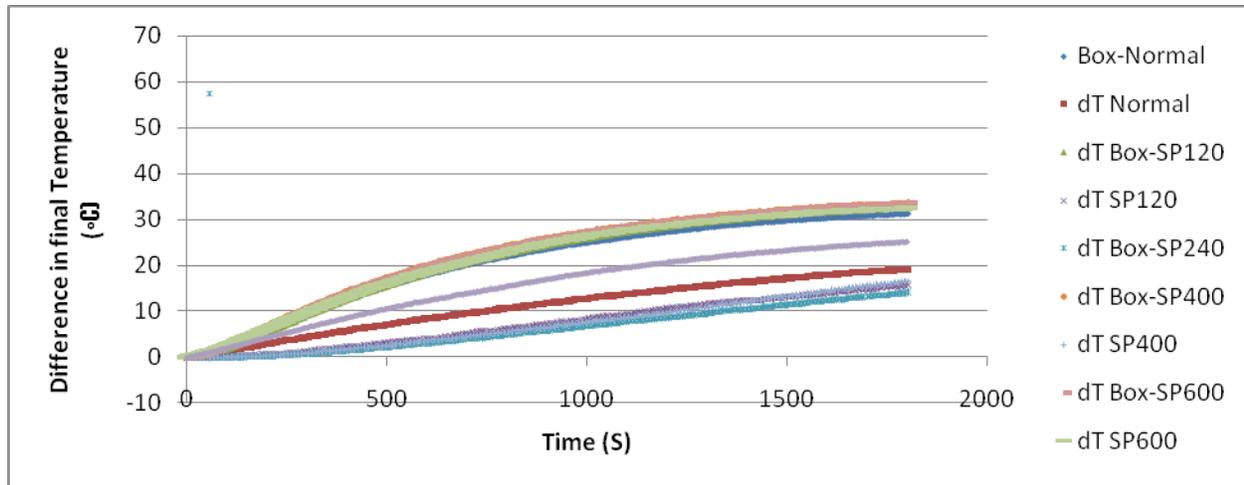
Figure 4: dTemperature V. Time

5.4 Surface Processing

Since the test specimens were prepared by hand, there were some variances in the surface

texture, most notably at the corners. In future tests, chamfering the edges will help make an even

surface for each test specimen. This experiment did not consider test specimens that were prepared

with CnC machines. In future tests I would suggest machining the surface of each test specimen with

different end mills, noting the feed rates and step-overs for repeatability. It is important to have an

even surface texture. Also it is important to have many test samples that were prepared under the

same conditions to increase repeatability and accuracy.

1.13 Surface Measurements

After compiling surface measurements from SP120 using the 5X, 10X, 20X, and 50X objective lenses, I decided that the 50X objective lens was best suited to take measurements. The use of the 50x lenses was suggested to me by my advisor.

1.14 Temperature Tests

Differences in final temperatures were observed among the test specimens. Of the test specimens, SP600 had the largest difference in temperature. This is most likely due to the darkening of the specimen during surface polishing. The specimen with the second highest temperature difference was test specimen, Normal. This is due to the surface not being polished using silicon based polishers . There was a noticeable difference in how fast the temperature rose and the final temperature of each specimen after 30 minutes. In future studies, analysis could be performed to calculate the total amount of heat transferred. This can then be used to obtain the amount of radiant heat transferred. One should also consider not painting the test box black. I observed in my experiments that the temperature of the box frequently exceeded the temperature of the test material. This caused heat to be transferred from the box to the test material convectively, which affected the test. After obtaining the amount of radiant heat transferred, one could then study how surface texture affects emissivity. "Properties of emissivity strongly depend on surface conditions… This uncertainty is largely due to the difficulty in characterizing and describing the surface conditions precisely". (P.889 TFS) Also further analysis could be done pertaining to surface texture and its effects on heat transfer. In the Appendix there are figures that display obtained temperature-time data and potential analysis of heat transferred.

Conclusions

1. Silicon based sand paper can be used to change the surface texture of aluminum to test. Pre-surface-processing techniques, such as chamfering of edges, can be implemented to promote an even surface texture for more accurate results.

2. The higher the magnification of the objective lens the more accurate the area-scale analysis.

3. Changing the surface texture of aluminum causes a change in the amount of heat transferred. The more rough the surface, the more heat that is transferred.

4. A precise measurement of the ratio of temperature change relative to surface roughness could not be obtained due to variables that could not be fully controlled during the test.

    a. The dark color of the test box introduced issues related to radiant heat transfer.

    b. Hand sanding the test samples introduced issues related to a lack of uniformity of surface texture for each sample and across the set of samples.

    c. Having single samples for each level of polish exacerbated issues related to unevenness of surface texture for each sample and across the set of samples.

Appendices

1.15 Issues and Solutions

During this experiment many obstacles had to be overcome. In this section I will review problem areas and ways in which I overcame them. The first issue I faced was finding a previous ASTM standard that would fulfill the needs for my experiment. One way to make this task easier would be to find a similar standard and contact the head of that committee. They are very knowledgeable about the standards and can direct you to the people that who developed the standards or who are currently using them. Another problem area was programming the VI used by LabView which controlled the data collection for the experiment. I went through many iterations before I reached the final product. I would suggest manipulating an existing VI to conform to the needs of the experiment before programming one from scratch.

Search Sites and Search Terms

1. Lexis Nexis

   1.1. Surface texture, surface texture and heat

2. Engineering Village

   2.1. Surface texture, surface texture and absorptivity, surface texture and convection, and surface texture and heat transfer

3. Science Direct

   3.1. Surface texture, surface texture and heat transfer, surface texture heat, texture gradient and heat

4. Jstore

   4.1. Surface texture, surface texture and heat

Acknowledgements

References

ASTM Standard E744, 2007, "Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications" ASTM International, West Conshohocken, PA

ASTM Standard E772, 2005, "Standard Terminology Relating to Solar Energy Conversion" ASTM International, West Conshohocken, PA, 2005

Cengel, Yanus A., Turner, Robert H., Cimbala, John M. Fundamentals of Thermal-Fluid Sciences. New York, New York, 2008

Kelly, George. BP Solar. 866-BP-SOLAR (866-277-6527), 2009