AIR QUENCHING OF ALUMINUM:
THE EFFECT OF QUENCH ORIENTATION AND AIR VELOCITY

A Major Qualifying Project Report

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by

Daniel Bylund

Ricardo Cruz

Stephen Kalach

Martin Tsoi

Approved:

Professor Yiming Rong, Advisor

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Abstract

Air quenching is a heat treatment process to control materials property of metals. The effects of air velocity and probe orientation during the air quenching process were investigated experimentally. An assembly was designed to remove the probe from a furnace and quickly reposition it around a single axis at predetermined angular increments. Experimental tests showed how these variables affect the heat transfer coefficient curves and their result on material properties.

Acknowledgements

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Introduction

While working with metal, it is often necessary to alter the material in a manner that will allow it to function properly in its desired use. This change in material properties can be the result of various procedures, usually consisting of heat treatment. The process known as quenching is one such procedure that typically results in an increase of strength and hardness at the cost of some ductility. This process consists of heating a material to a critical temperature and then cooling (quenching) the part by submersion in water or oil, or by forced air or gas. When the part is heated near its melting temperature the alloying constituents are in solution, rapidly quenching the part serves to lock the alloys in a crystalline structure, which is stronger than the original. A rapid quench, however, results in residual stresses in a part as well as brittleness. The desired material property is controlled by the rate of cooling of the part. Therefore in order to achieve the desired material properties it is necessary to understand what factors effect how a part is cooled.

1 Background

1.1 Air Quenching

Air quenching is used as a means to limit the residual stresses as well as the brittleness that occurs during the quenching process. Rapid quenching also has a tendency to create distortions due to the stresses, especially if the cooling is non-uniform over the surface of the part, air quenching may be used to remedy this. For improving fatigue life some residual stress can be advantageous and can be achieved through the comparatively slower cooling rate of air quenching.

Cooling rate is governed by the Heat Transfer coefficient (HTC), which is a function of the heat flux and the temperature gradient. Since the HTC is the critical factor for achieving desired material properties while air quenching, understanding some of its influences is a necessity. Some of these influences include, size and material to be quenched, air velocity, air temperature, type of gas being used for quenching, surface quality (machined, cast, etc.), and the orientation of the material in the stream of air. Factors proving to be relatively insignificant are the relative humidity and the air temperature however they do still have an effect. Orientation of the part presumably has significance, but its effects have yet to be studied in detail.

The cooling rate is governed by the heat transfer coefficient, which can be found experimentally (for small geometries) by the equation below (where m is the mass; Cp is the specific heat; T is the temperature at a given time of the material; Tair is the temperature of the Air; and A is the surface area of the material). This formula calculates the average HTC over the surface of the part.

$$h_c = -\frac{m \cdot C_p(T)}{A(T - T_{air})} \cdot \frac{dT}{dt}$$

1.2 Previous Studies

In order to better understand how to best study what affects air quenching previous studies were examined. As this project is low budget and does not use sophisticated equipment similar experiments were studied. The first study was an MQP from 2002 on the gas quenching of steels. The parameters which they studied were quench medium (helium, argon, and air) and the velocity of quench gases. A small setup was used; a pneumatic cylinder holding a test probe lowered the probe into a furnace, and then lowered the probe once heated to 850°C into a chamber which was filled with a quench gas. Inside the chamber two opposing fans each capable of a velocity of 4m/s were used to create gas flow around the probe.

Further in order to calculate the heat transfer coefficient the group used a small probe which created a biot number of less than .1. This creates a condition where the temperature from the center of the probe to the outer surface does not vary more than 5%. This is essential as it allows the use of only one thermocouple placed at the center of the probe and permits the use of a simple inverse calculation of the heat transfer coefficient.

The experiment found that helium was the best quench medium. In addition the use of two fans also created the best condition for heat transfer for every medium. Thus it was found that the highest heat transfer coefficient could be achieved with two fans with helium as a quench medium, conversely using argon as the quench medium while using no fans was found to create the lowest heat transfer coefficient.

2 Experimental Plan

The table below represents the experimental plan. Aluminum 319 is heated to 500°C and is then removed from the furnace and quenched from a unidirectional fan source. The aluminum tested will have two different surface finishes, machined and casted. Each different surface finish will be tested at several different quench orientations including 90°, 70°, 45°, 20°, and 0°. At each orientation we will test several different quench air speeds including 5.0m/s, 7.5m/s , 9.8m/s, 13.7m/s, and 17.4m/s. These air speeds correspond to voltages on the variac of 35V, 45V, 50V, 63V, and 110V, respectively. This totals a total number of 29 experimental variables with each variable being tested two times for a total number of 58 experiments. During each experiment the necessary data will be acquired to calculate the HTC, which will be used in our analysis.

Experiment Conditions	Probe	Surface Finish	Air Temp (°C)	Probe Incline	Air Velocity (m/s)	Air Pressure (hpa)	Relative Humidity	# of Tests	Remarks
1	319 Aluminum	Casting		Horizontal	17.4			2	
2					13.7			2	
3					9.8			2	
4					7.5			2	
5					5			2	
6				20 Degrees	17.4			2	
7					9.8			2	
8					5			2	
9				45 Degrees	17.4			2	
10					9.8			2	
11					5			2	
12				70 Degrees	17.4			2	
13					9.8			2	
14					5			2	
15				Vertical	17.4			2	
16					13.7			2	
17					9.8			2	
18					7.5			2	
19					5			2	
20	319 Aluminum	Machined		Vertical	17.4			2	
21					13.7			2	
22					9.8			2	
23					7.5			2	
24					5			2	

Figure 1: Experimental Matrix

3 Procedure

3.1 Material Tested

The material chosen for the probe was 319 Aluminum, as this material's properties are favorable for our specific use and fabrication needs. Since some of the probes require machining, 319 Aluminum is acceptable due to its six percent of silicon. Also, it has good ductility and fatigue life, and was available in casting. It has an ultimate tensile strength of 250MPa and tensile yield strength of 165MPa. The material is also capable of heat treatment, which is not a common trait for all aluminum alloys. Heat treatable aluminum alloys commonly combine one or more of the following elements; zinc, silicon, magnesium and/or copper. The table below shows the usual chemical composition ranges of aluminum alloys including 319.

Table 1: Chemical Compositions of Common Aluminum Alloys, %

Alloy	Type of Mold	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other
201	S or P	0.10	0.10	4.0-5.2	0.20-0.50	0.20-0.50	-	-	-	0.15-0.35	0.10
319	S or P	5.5-6.5	0.60	3.0-4.0	0.10	0.10	-	0.10	0.10	0.20	0.20
356	S or P	6.5-7.5	0.13-0.25	0.10	0.05	0.30-0.40	-	-	0.05	0.20	0.15
A356	S or P	6.5-7.5	0.12	0.10	0.05	0.30-0.40	-	-	0.05	0.20	0.15
535	S	0.10	0.10	50.05	0.10-0.25	6.6-7.5	-	-	-	0.10-0.25	0.15

3.2 Probe Design Requirements

In order to testify the relationship between heat transfer coefficient with surface finishing and shape in air-quenching, five different probes were designed and fabricated for this goal. All probes are made of aluminum 319 by sand casting, and some probes undergo several machinery processes to meet the specific design requirement. Each probe is defined by its size, shape, and type of surface finish.

3.2.1 ½" diameter cylindrical sand-casting probe

This probe is cut into an appropriate length by hydraulic horizontal bandsaw from a ½" diameter and 12" length bar stock. HAAS TL-1 CNC lathe is used to fabricate the

OD-thread and the thread relief. The OD-thread has a design specification — 5/16” diameter, 2A, and 24 teeth per inch.

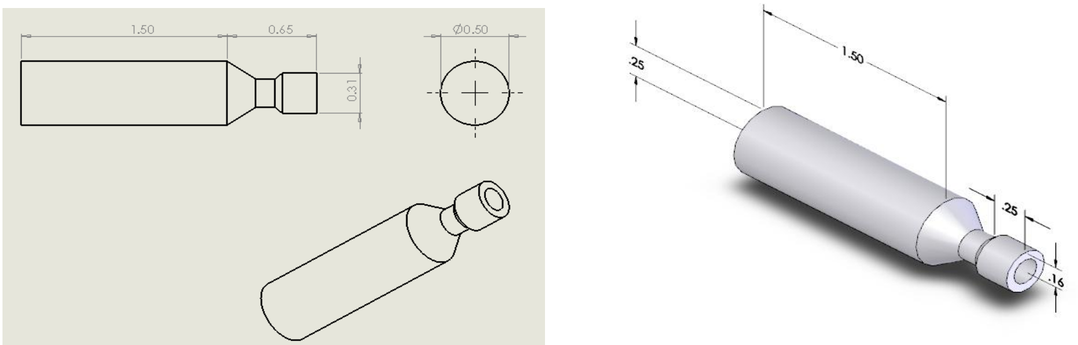

Figure 2: ½” diameter cylindrical sand-casting probe

3.2.2 1” diameter cylindrical sand-casting probe

This probe is cut into an appropriate length by hydraulic horizontal bandsaw from a 1” diameter and 12” length bar stock. HAAS TL-1 CNC lathe is used to fabricate the OD-thread and the thread relief. The OD-thread has a design specification — 5/16” diameter, 2A, and 24 teeth per inch.

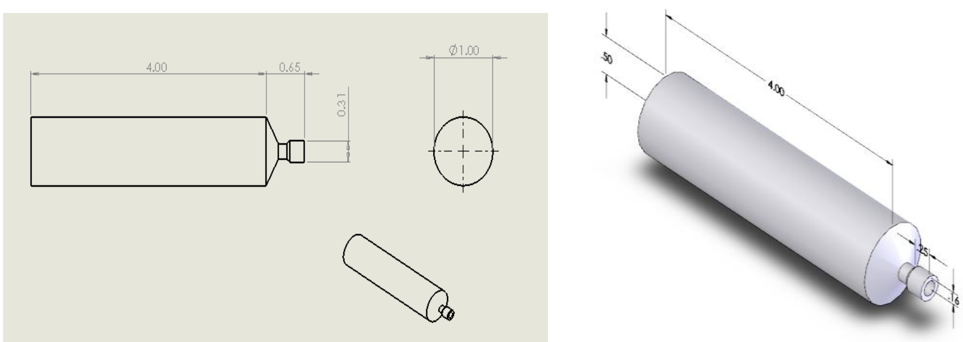

Figure 3: 1” diameter cylindrical sand-casting probe

3.2.3 ¼” diameter cylindrical machined probe

This probe is cut into an appropriate length by hydraulic horizontal bandsaw from a ½” diameter and 12” length bar stock. HAAS TL-1 CNC lathe is used to fabricate the ¼” machined surface, OD-thread and thread relief. The OD-thread has a design specification — 5/16” diameter, 2A, and 24 teeth per inch.

3.2.4 ¼” diameter ball sand-casting probe

This probe is sand casted into a spherical shape. A manual drill press is used to drill a 5/16” diameter hole, then a manual tapper for the ID thread.

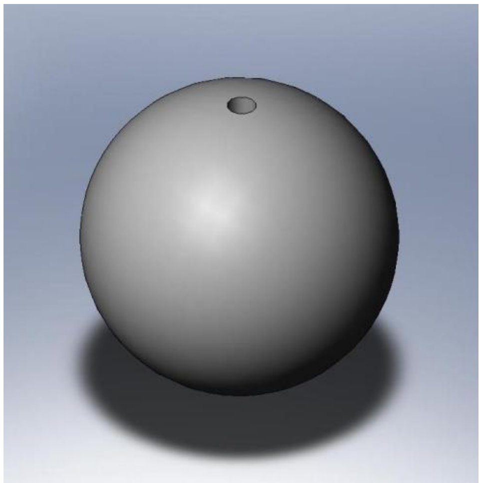

Figure 4: ¼” diameter ball sand-casting probe

3.2.5 4” by 4” by 1” Plate Sand-Casting Probe

This probe is sand casted into a square plate shape. A manual drill press is used to drill a 5/16” diameter hole, then a manual tapper for the ID thread.

Figure 5: Plate Sand-Casting Probe

3.3 Assembly Design

The purpose of the assembly design will be to study the effect of work piece orientation, air speed velocity and surface finish on the heat transfer coefficient. In order to do this the following design requirements will be used.

3.3.1 Design Requirements

1. *Air velocity must be controlled.*

This will be done using a variac to control the voltage of the fan. With a maximum of 110V and a minimum of 35V allowed. Within this range, we want 5 points to collect data. The following table shows the voltages and the approximate wind velocity that correlates with that voltage.

Table 2: Variac Voltage for Desired Air Speed

110V	17.4 Meters/Second
63V	13.7 Meters/Second
50V	9.8 Meters/Second
45V	7.5 Meters/Second
35V	5.0 Meters/Second

2. *Orientation of the piece must be controlled*

An assembly has been designed and will be manufactured to pneumatically drop and recover the probe from the furnace, mimicking the current the procedure. An added feature of the new assembly will be to rotate 90 degrees about the point of the probe to study what effect orientation has on the probes HTC and therefore, what effect orientation has on the material properties of the probe.

3. *Must be capable of measuring:*
    - Ambient Temperature
    - Temperature of the piece
    - Air speed
    - Pressure
    - Humidity

The temperature of the piece and the ambient temperature are being measured and recorded into the Labview program (creates virtual instruments for the recording of data). A space heater allows control of the ambient temperature. An instrument is also monitoring the pressure and humidity of the small room, and if humidity is outside acceptable tolerances, a humidifier is available to use.

4. *Must have reasonably uniform air flow around the piece*

The area of the fan is much larger than the probe and is at an acceptable level of variation.

5. *Furnace capable of heating the piece to the desired temperatures.*

The specific furnace is capable of heating the aluminum to 500 degrees.

6. *Piece must move from furnace directly into position to be air cooled*

The new assembly repeats the use of a pneumatic actuator to lower and raise the probe from the furnace, directly into the path of the fan.

3.3.2 Design and fabrication

A simple table set up was used: the furnace would be located under the table while the fan and orientation arm were placed on the table. A pneumatic cylinder attached to the arm would lower the aluminum probes into the furnace through a hole in the table. Once heated the probe would be raised and the arm would be adjusted to the correct angle. The fan is attached to a variac which is used to control its voltage; in turn this controls the air velocity from the fan. Two thermocouples are used, one inside the probe and one located directly in front of the fan to measure the ambient temperature. A commercial weather station is used to measure the humidity and to monitor room temperature. Labview is used in conjunction with these thermocouples to record the temperature of the probe as well as the ambient temperature in reference to time. This will later be used to calculate the heat transfer coefficient

The orientation arm had to be designed by scratch. We knew the sizes of the pneumatic cylinder, its extending arm, and where the probe would sit if the pneumatic arm was fully retracted. Based on this we thought of a simple rotation arm design created in Solidworks and shown below. The arm would be attached to the table and could freely rotate about one axis. This axis was purposely placed to be exactly in line with the bottom of the probe when it is fully retracted. This keeps the probe at a constant distance from the fan when its orientation is adjusted. The adjustment of the arm uses a simple pin system; the arm can freely rotate and pins are used to stop its movement as to set the probe at certain angles. The pin is placed manually to keep the system as simple as possible.

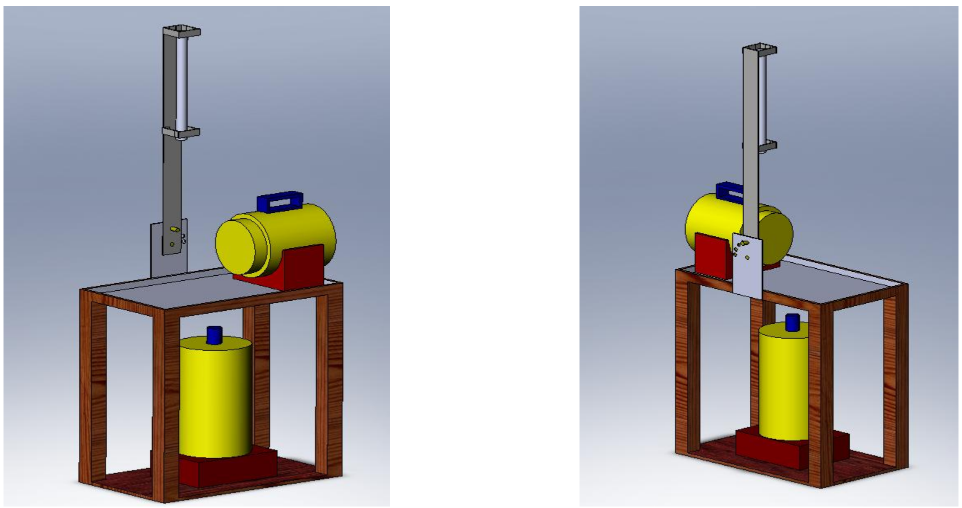

Figure 6: Assembly Design

Figure 7: Assembly Design

4 Results and Analysis

The graphs shown below, Figures 8-21, represent all our data collected during the experimentation process, as well as the calculations of the heat transfer coefficient for each experiment. Since the heat transfer coefficient is a function of both the probe temperature and in this case the room temperature, our data for room temperature is also reflected in these graphs as part of the HTC. The heat transfer coefficients were calculated using the Matlab program discussed in the Methodology section to evaluate the equation for the HTC shown in the background. Each graph above plots the Heat Transfer Coefficient on the vertical axis and the probe temperature on horizontal. According to the results the HTC remains relatively constant as the probe temperature changes; changing less than 10 $w/m^2/k$ for each test, however it is affected greatly by air velocity as well as probe orientation.

The first three graphs, Figures 8-10, show the HTC as a function of probe temperature for three different air speed velocities, 5 m/s , 9.8 m/s, and 17.4 m/s. The colored lines on each graph correspond to the different cast probe orientations, as well as including the vertical orientation for the machined probe, as this was the only test completed for the machined probe. From these graphs the general trend in the effect probe orientation has on the HTC can be deduced.

The next six graphs, Figures 11-16, represent the probes at the five different probe orientations we studied. The colored lines on these charts represent the air velocities tested. For the vertical and horizontal orientation there were five airspeeds tested instead of three, and these are shown. Figure 16 represents the five different airspeed velocities, 5 m/s, 7.5 m/s, 9.8 m/s, 13.7 m/s, and 17.4 m/s, for the machined probe. From these figures the effect air velocity has on the HTC can be seen.

Since we only did tests for the vertical orientation of the machined probe, the last five graphs, figures 17-21, represent the difference in the HTC between the cast probe and the machined probe, for the five air velocities, at this orientation. From these graphs the effect on the HTC of two different surface finishes, cast and machined, can be seen.

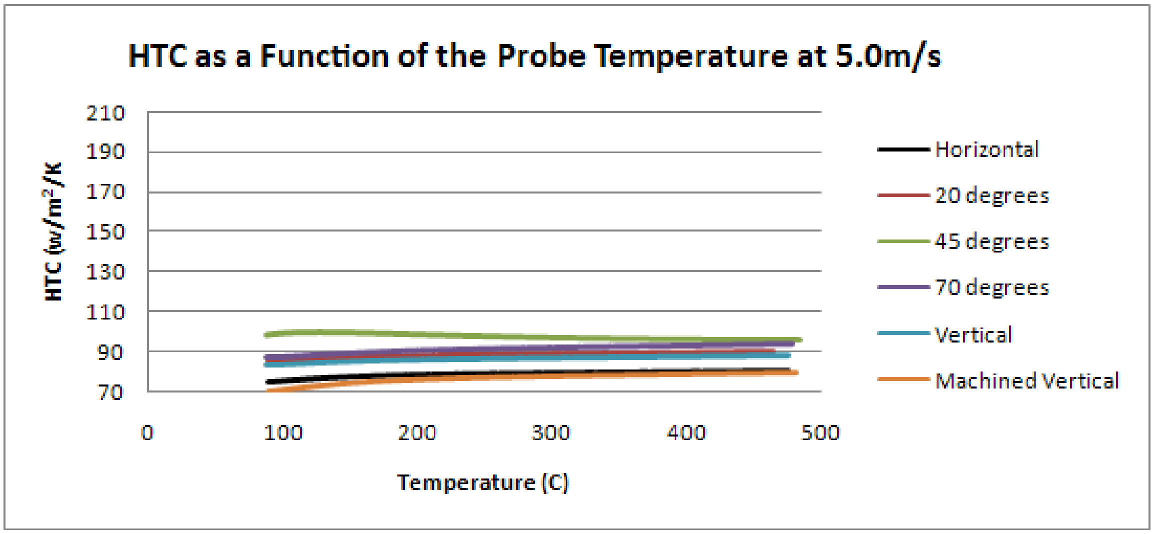

Figure 8: HTC as a Function of the Probe Temperature at 5.0m/s

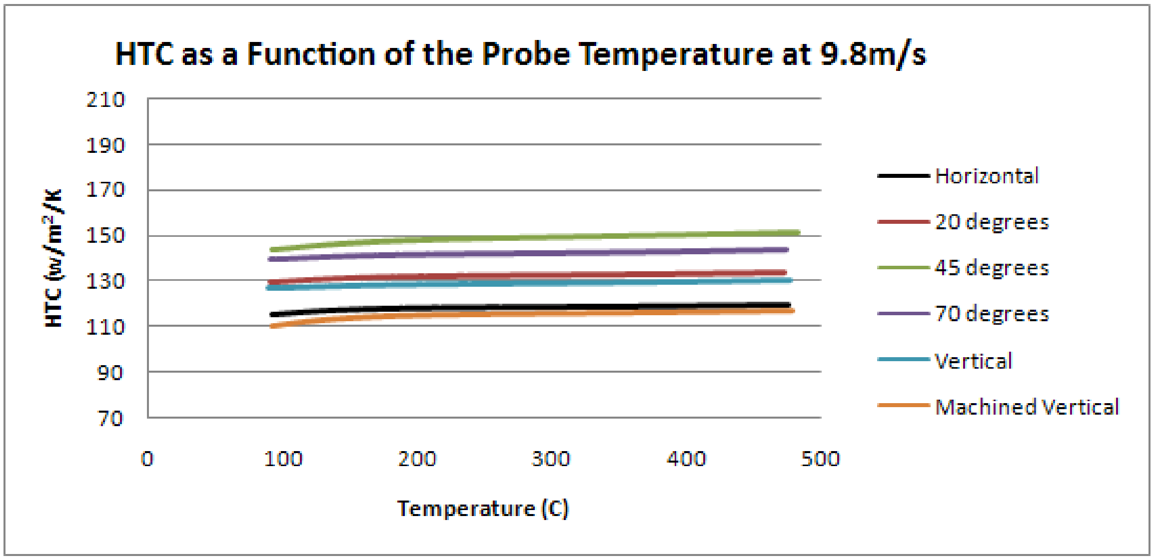

Figure 9: HTC as a Function of the Probe Temperature at 9.8m/s

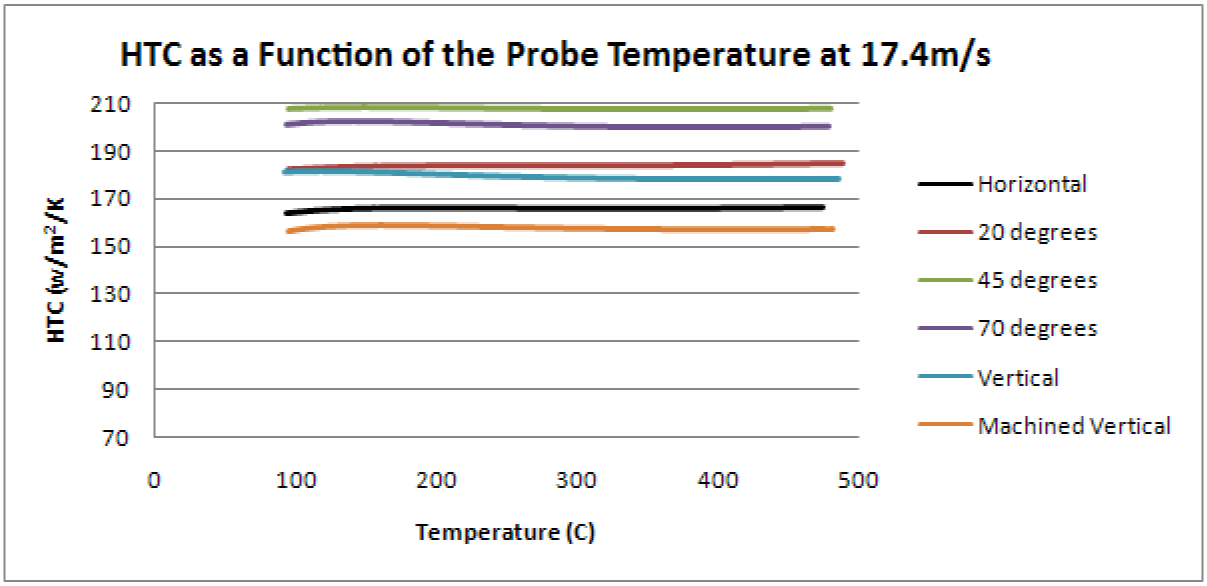

Figure 10: HTC as a Function of the Probe Temperature at 17.4m/s

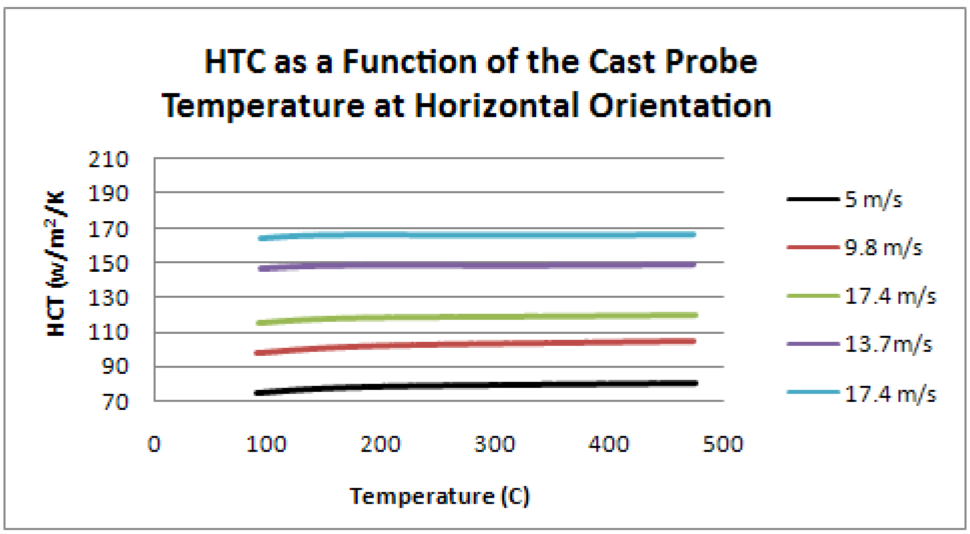

Figure 11: HTC as a Function of the Cast Probe Temperature at Horizontal Orientation

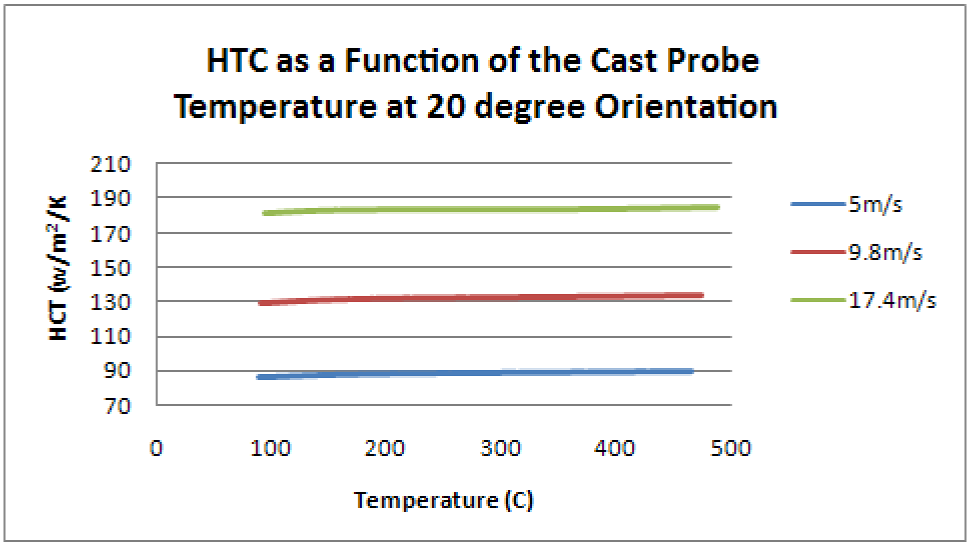

Figure 12: HTC as a Function of the Cast Probe Temperature at 20° Orientation

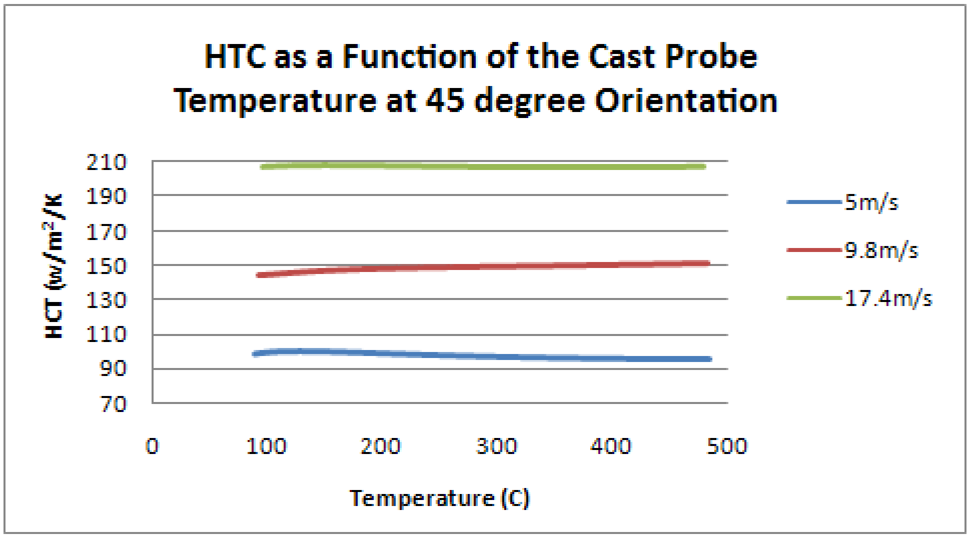

Figure 13: HTC as a Function of the Cast Probe Temperature at 45° Orientation

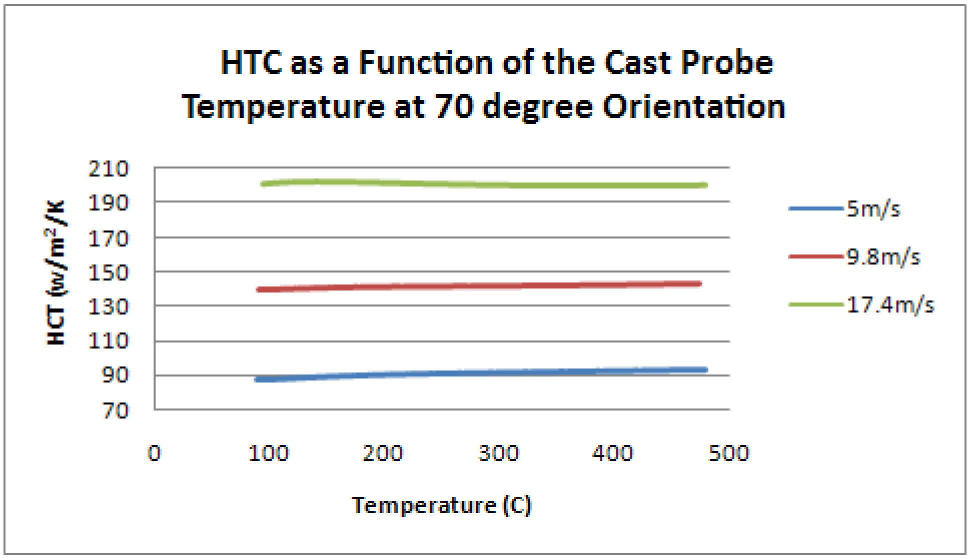

Figure 14: HTC as a Function of the Cast Probe Temperature at 70° Orientation

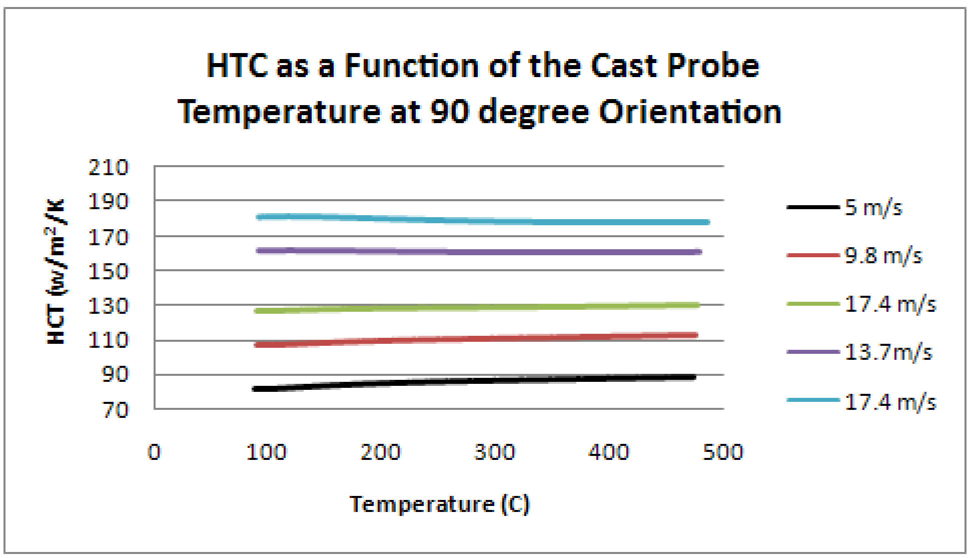

Figure 15: HTC as a Function of the Cast Probe Temperature at 90° Orientation

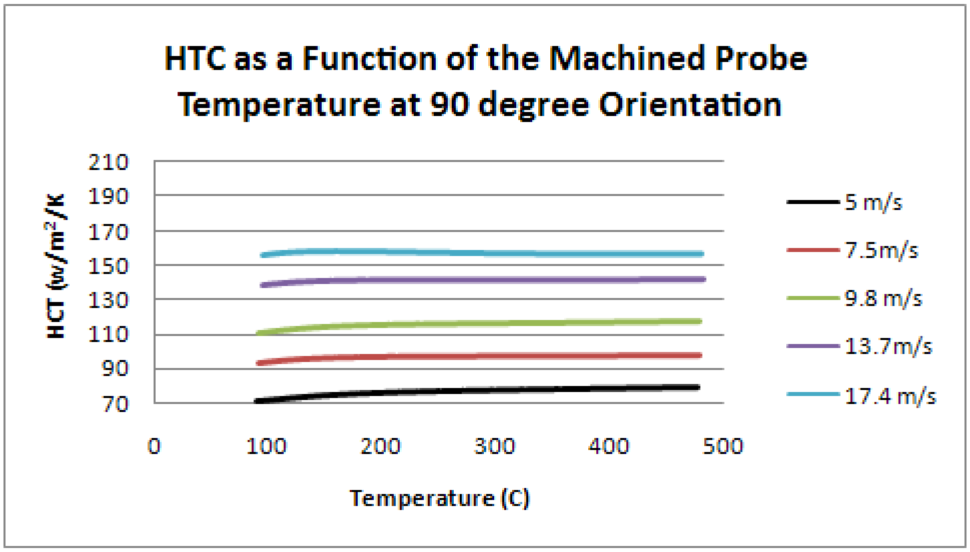

Figure 16: HTC as a Function of the Machined Probe Temperature at 90° Orientation

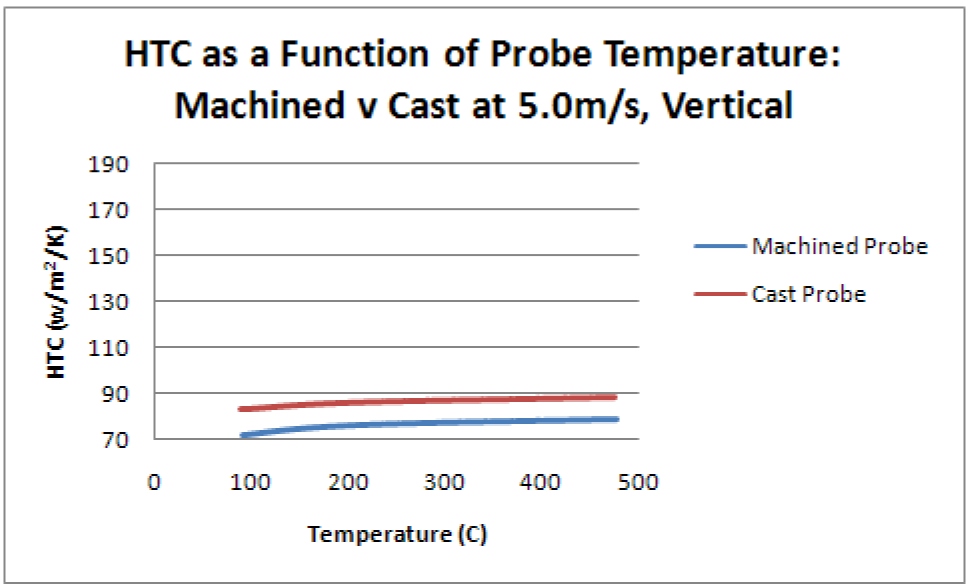

Figure 17: HTC as a Function of Probe Temperature: Machined v. Cast at 5.0m/s, Vertical

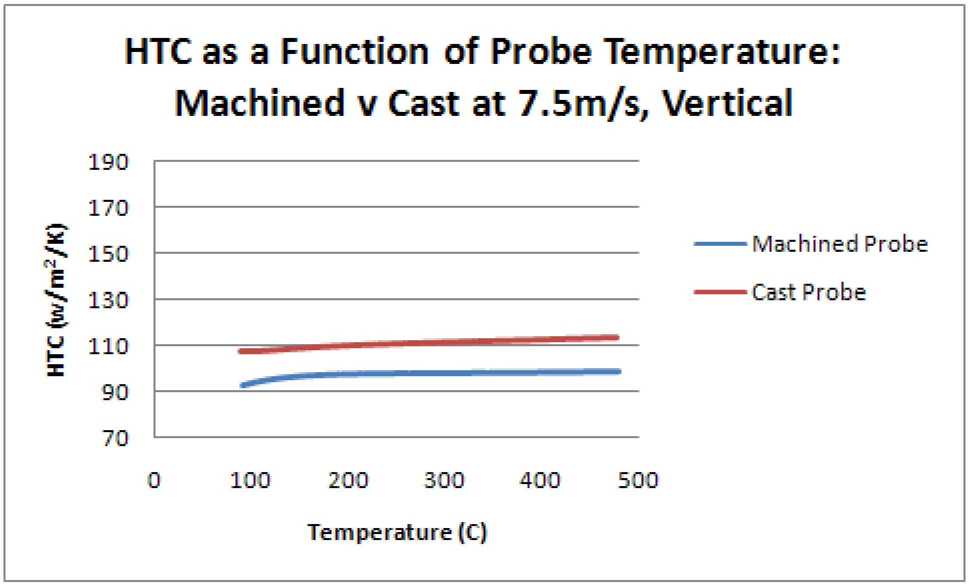

Figure 18: HTC as a Function of Probe Temperature: Machined v. Cast at 7.5m/s, Vertical

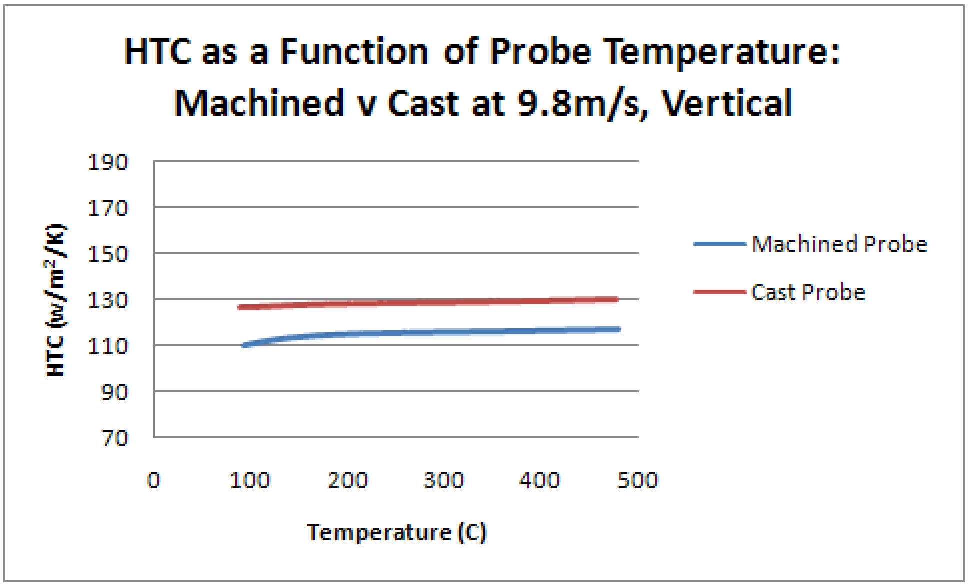

Figure 19: HTC as a Function of Probe Temperature: Machined v. Cast at 9.8m/s, Vertical

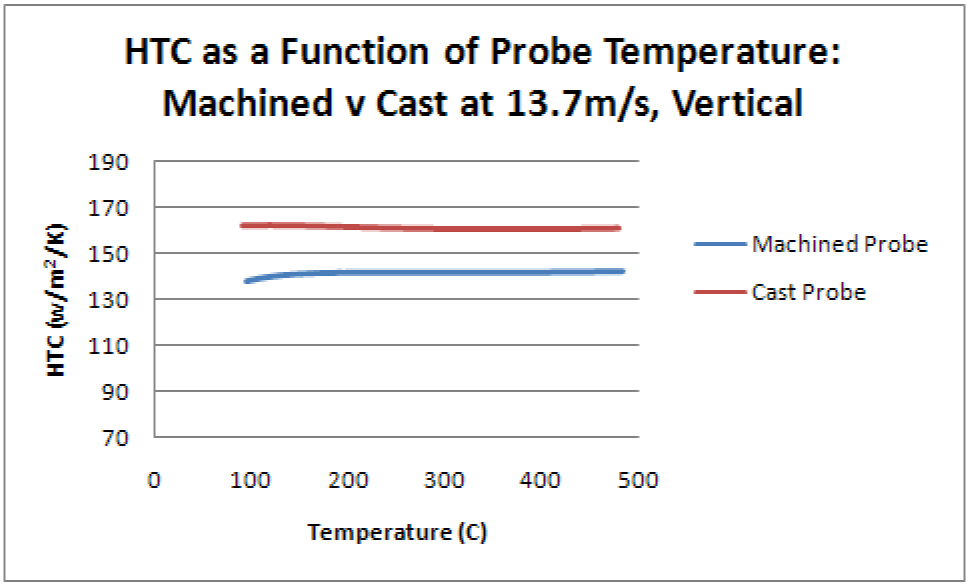

Figure 20: HTC as a Function of Probe Temperature: Machined v. Cast at 17.7m/s, Vertical

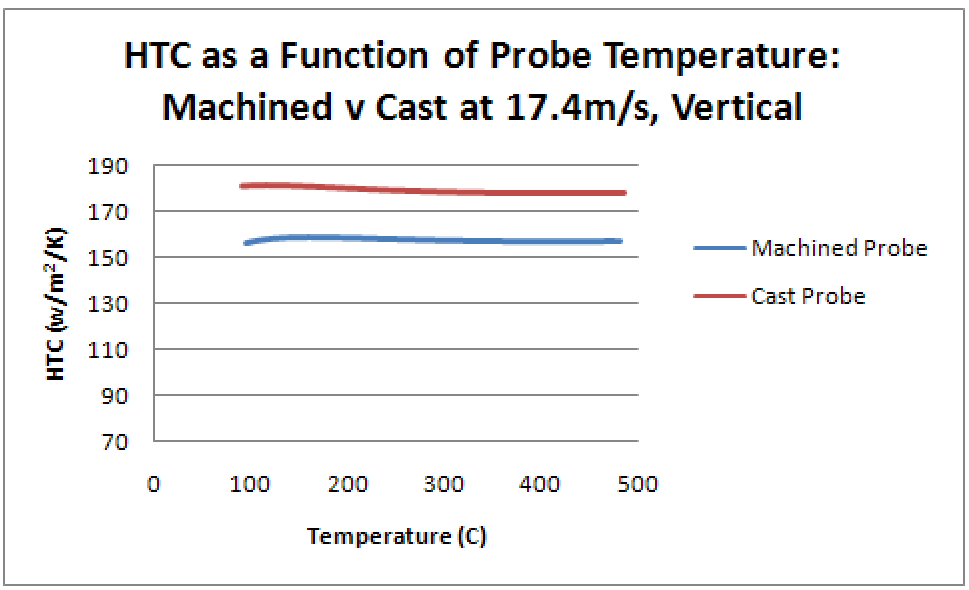

Figure 21: HTC as a Function of Probe Temperature: Machined v. Cast at 17.4m/s, Vertical

5 Conclusion

Air velocity was the most important factor in determining the HTC. The greatest air velocity produced in this experiment was 17.4 m/s, and always caused the highest HTC. Consequently, the lowest air velocity of 5 m/s always produced the lowest HTC.

In experimentation, it was found that the 45 degree orientation had the highest HTC, followed by the 70 degree orientation. The 20 degree orientation and the vertical orientation were very close when comparing the HTC, and the lowest value HTC was the horizontal orientation.

Surface finish did prove to be a factor, as it was recorded that the cast probe had a higher HTC than the machined probe, and the difference was always recorded as a stable margin. Both the machined and cast probes followed the same trends, but the cast probe just had a higher value, which varied from about 10 w/m^2/K to about 20 w/m^2/K, again, depending on the air velocity which the probe was exposed to. w/m^2/K is the dimension of the HTC.

It has been hypothesized that surface area exposed, and the resulting air flow over the remaining area of the probe has been the main factor in the experimental testing. That was the first hypothesis to be developed as the main question of the experiment was focused on the different orientations. As it was discovered that the 45 degree angle resulted in the highest HTC, and the horizontal orientation resulted in the lowest HTC, the possible differences were examined. It was thought that the horizontal orientation exposed the least amount of area to the direct air path of the fan, and as more data was gathered and studied, the proposed trend became more probable. It cannot be said with absolute certainty that surface area exposed to the direct air path of the fan is the only factor without the use of Computational Fluid Dynamics. The use of CFD would allow correct measurement of surface area and the resulting air flow over the rest of the probe.

The data gathered from this experiment can be used in industry as a reference of the how to achieve the desired HTC for aluminum 319 by air quench, and consequently how to achieve the desired material properties. Each variable of air velocity, orientation, and surface finish can be combined to achieve a unique HTC. Another use of this data would again make use of CFD programs. Using the data already gathered, the Computational Fluid Dynamic programs can use the known data as a reference. If industry would then like to experiment with different variables, using the reference of CFD programs, then changing the desired variables, the program would be able to predict what it's HTC, and therefore be able to predict it's material properties without actually going through the process of air quenching.

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