March 2008

Air Quenching of Aluminum: The affect of quench orientation and air velocity

Stephen P. Kalach
Worcester Polytechnic Institute

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

A Major Qualifying Project Report

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Daniel Bylund

Ricardo Cruz

Stephen Kalach

Martin Tsoi

Approved:

Professor Yiming Rong, Advisor

Date: March 12, 2008

Table of Contents

Table of Figures

Table of Tables

Introduction

1 Background

1.1 Air Quenching

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. Therefore the desired material property is controlled by the rate of cooling of the part.

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.

1.3 Heat Transfer Coefficient Calculation

(Equations involved in calculating the HTC in our experiments)

2 Case Studies

(Includes how production air quench systems work)

3 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 4.8m/s, 7.5m/s , 10.5m/s, 15m/s, and 18m/s. A separate set of tests will be done for a larger casted aluminum probe at the 90° angle with the same quench air speeds. This totals a total number of 55 experimental variables with each variable being tested 3 times for a total number of 165 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 Temperature (°C)	Probe Incline	Air Velocity (m/s)	Air Pressure (hpa)	Relative Humidity	# of Tests	Remarks
1	319 Small Cylinder	Casting	15+2	Horizontal	18			3	
2					?			3	
3					10.5			3	
4					?			3	
5					4.8			3	
6				20 Degrees	18			3	
7					?			3	
8					10.5			3	
9					?			3	
10					4.8			3	
11				45 Degrees	18			3	
12					?			3	
13					10.5			3	
14					?			3	
15					4.8			3	
16				70 Degrees	18			3	
17					?			3	
18					10.5			3	
19					?			3	
20					4.8			3	
21				Vertical	18			3	
22					?			3	
23					10.5			3	
24					?			3	
25					4.8			3	
26			15+2	Horizontal	18			3	
27					?			3	
28					10.5			3	
29					?			3	
30					4.8			3	
31				20 Degrees	18			3	
32					?			3	
33					10.5			3	
34					?			3	
35					4.8			3	
36				45 Degrees	18			3	
37					?			3	
38					10.5			3	
39					?			3	
40	319 Small Cylinder	Machined			4.8			3	
41				70 Degrees	18			3	
42					?			3	
43					10.5			3	
44					?			3	
45					4.8			3	
46				Vertical	18			3	
47					?			3	
48					10.5			3	
49					?			3	
50					4.8			3	
51	319 Big Cylinder	Casting	15+2	Vertical	18			3	
52					?			3	
53					10.5			3	
54					?			3	
55					4.8			3	

4 Procedure

(How we went about preparing and executing the MQP)

4.1 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

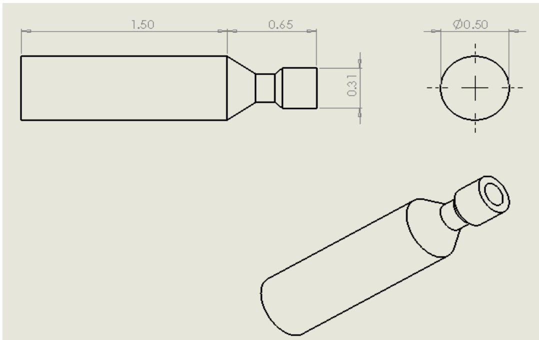
4.2 Probe Design Requirements

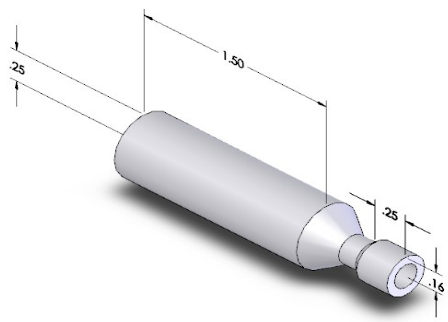
In order to testify the relationship between heat transfer coefficient with surface finishing and shape in air-quenching, five different probes were designed and fabricated for this goal. All probes are made of aluminum 319 by sand casting, and some probes undergo several machinery processes to meet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

4.2.1 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

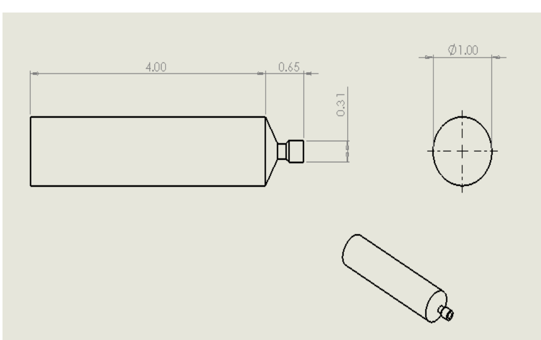
OD-thread and the thread relief. The OD-thread has a design specification — 5/16” diameter, 2A, and 24 teeth per inch.

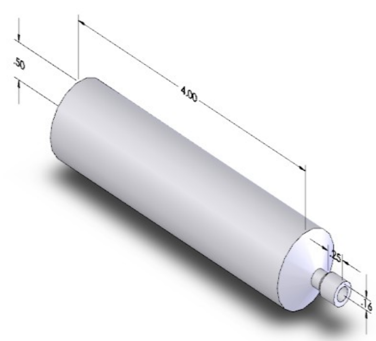




4.2.2 1” diameter cylindrical sand-casting probe

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.





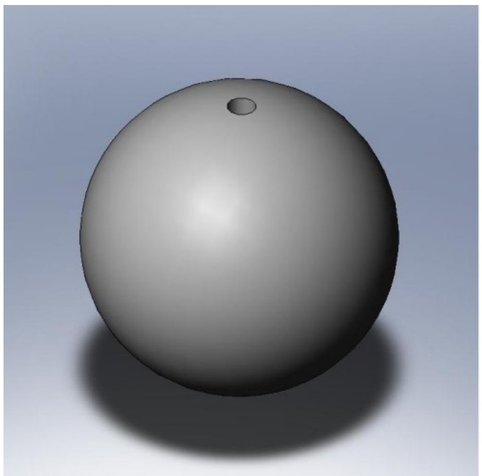
4.2.3 ¼” diameter cylindrical machined probe

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.

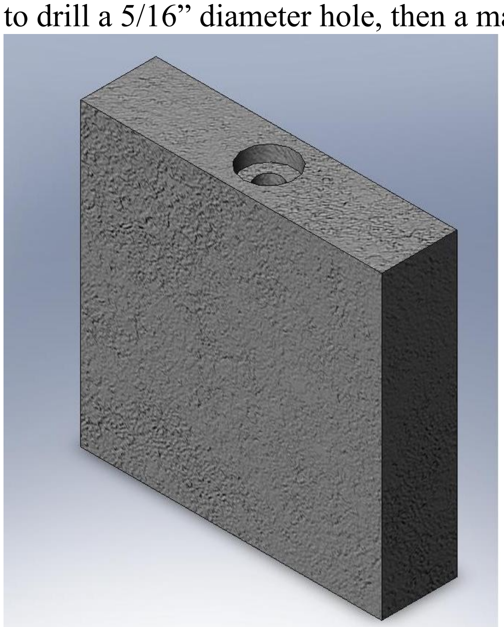
4.2.4 ¼" diameter ball sand-casting probe

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.



4.2.5 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.



4.3 Assembly Design

4.3.1 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.

110V	18 Meters/Second
60V	15 Meters/Second
50V	10.5 Meters/Second
45V	7.5 Meters/Second
35V	4.8 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.

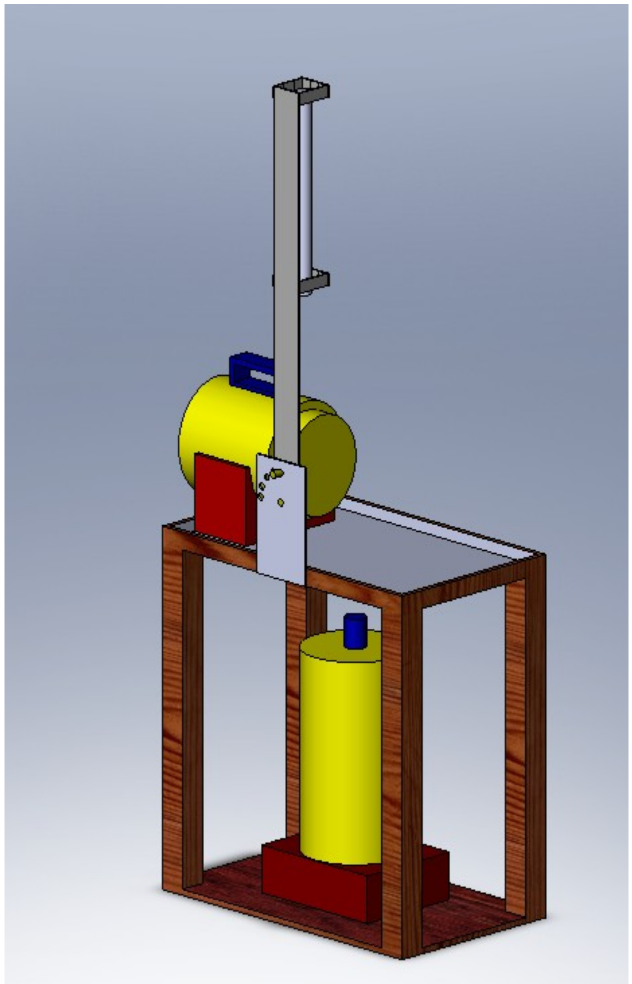
6. Piece must move from furnace directly into position to be air cooled

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.

4.3.2 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.



(How the orientation arm was fabricated)

5 Analysis

(How tested variables could affect HTC)

6 Results

(Plots, tables)

7 Experimental Analysis

(How the tested variables affected the HTC)

8 Conclusion