THE EFFECT OF KEY MICROSTRUCTURE FEATURES ON THE MACHINING

OF AN ALUMINUM-SILICON CASTING ALLOY

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ABSTRACT

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The need to increase the cutting tool life when machining A356 has led to the continuous development of strategies to accomplish this goal. It has been proposed the modification of the microstructure of this type of alloy as a strategy for ensuring a longer tool life during machining. Throughout modification of the silicon phase it is possible to enhance the mechanical properties of the alloy, establishing in this way, the linkage among microstructural characterization (i.e., unmodified vs. modified), mechanical properties, and tool life. If modification of the silicon phase leads to an enhancement of the mechanical properties, then it is expected a reduced wear on the cutting tool drilling in the modified structure, resulting in a higher number of drilled holes prior to tool failure than that experienced in an unmodified structure.

I.   INTRODUCTION

Aluminum is the most abundant metal in the earth's crust and offers good

conductive and thermal properties. It can be alloyed with other elements, such as silicon,

to increase its strength, reduce weight, and improve machinability. Many of the common

aluminum casting alloys contain enough silicon to cause the eutectic reaction, giving the

alloys a low melting point, good fluidity and good castability. Fluidity can be defined as

the ability of the liquid metal to flow through the mold without prematurely solidifying

and castability refers to the ease with which a good casting is made from the alloy.

The production of semifabricated products utilizes three different types of

aluminum, namely super purity, commercial purity, and alloys. Alloys are used for

producing castings or fabricating wrought products. The alloys used for castings contain

a greater amount of alloying additions than those used for wrought products. The addition

of alloying elements has the effect of strengthening the wrought alloys and improving the

castability of the casting alloys. Wrought alloys are generally used for further fabrication,

such as rolling, forging, and extrusion. Casting alloys are used for cast parts and have the

flow characteristics favorable for this purpose (1).

The wrought aluminum alloy designation system consists of four numerical digits.

The first digit defines the major alloying class. The second defines variations in the

original basic alloy. The third and fourth digits designate the specific alloy within the

2

series. The cast aluminum designation system also has four digits, but a decimal point between the third and the fourth digit is used to identify alloys in the form of castings or foundry ingot. The first digit indicates the alloy group, which is determined by the alloying element present in the greatest mean percentage. The second and third digits identify the specific aluminum alloy. The fourth digit indicates the product form: xxx.0 indicates castings, and xxx.1 indicates ingot. A letter before the numerical designation indicates modification of the original alloy or an impurity limit. Figure 1 shows the meaning of the first of the four digits in the alloy designation system (2).

Wrought alloy designation system		Cast alloy designation system	
Alloy	Main alloying element	Alloy	Main alloying element
1xxx	Mostly pure aluminum	1xx.x	Pure Al, 99.00% max
2xxx	Copper	2xx.x	Copper
3xxx	Manganese	**3xx.x**	**Silicon, with added Cu or Mg**
4xxx	Silicon	4xx.x	Silicon
5xxx	Magnesium	5xx.x	Magnesium
6xxx	Magnesium and silicon	7xx.x	Zinc
7xxx	Zinc	8xx.x	Tin
8xxx	Other elements (iron or tin)	9xx.x	Other elements
9xxx	Unassigned	6xx.x	Unused series

Figure 1. Main Alloying Elements in the Wrought and Cast Alloy Designation System.

Aluminum-silicon alloys are widely used for shape castings due to their high fluidity, ease of casting, low density, and controllable mechanical properties. They comprise aluminum with silicon additions of up to 11% (hypoeutectic), 11 to 13% (eutectic) or over 13% (hypereutectic) (3). Specifically, A356.0 (i.e., silicon with added Mg) casting alloy is highly used within the automotive, aerospace, and military industries.

In 1990, Gruzleski and Closset said that, "properties of A356.0 and A357.0 alloys are very attractive for many automotive and aircraft part applications. In Australia and North America, A356.0 cast wheels are normally modified with strontium to obtain maximum tensile strength and ductility after heat treatment (4). In addition and as a reference, more than 50% of the new cars sold on the European market are equipped with A356 crankcase diesel engines, which put high levels of thermo-mechanical stress on their cylinder heads (5).

The need to increase the cutting tool life when machining A356 has led to the development of many strategies. One of them, as many studies suggest, is the use of cutting fluids as a way to lubricate and cool down the tool. However, there is a lack of literature regarding the importance that the microstructure of the casting has for ensuring a longer tool life during machining.

Some parameters to establish a good quality casting are: modification rating, dendrite arm spacing (DAS), and porosity. Although grain refinement is often mentioned in the aluminum casting literature, it will not be taken into account because the properties of cast alloys which contain a large fraction of eutectic, such as the Al-Si alloys, are much less dependent on grain sizes, and grain refinement of these alloys is of diminished value. It is the brittle eutectic silicon phase which determines their properties, and hence processes of eutectic modification become much more important than grain refinement (6).

The microstructural modification of hypoeutectic and eutectic Al-Si alloys, which fall in the 5%-13% Si range, is not a choice, but a must when producing high quality

castings. The A356 alloy falls in that range. Alloy composition is important for the control of castability as small variations have been shown to not only affect the final microstructure of a casting, but also its tendency for porosity formation. Modification of Al-Si alloys with trace amounts of strontium (Sr) and sodium (Na) is an accepted means of enhancing the material properties (7).

The Al-Si eutectic is an irregular and coupled eutectic and silicon is the leading phase in unmodified alloys. However, the silicon morphology can be changed into a refined fibrous structure through modification treatment which can improve the mechanical properties of the alloy (8). Some of these properties, such as ultimate tensile strength (UTS), yield strength, and elongation, can be easily related to the change in silicon size and morphology from a relatively coarse acicular to a fine fibrous form found on modification (9). Thus, during the solidification process, the aluminum and silicon solidify as separate entities. While the silicon solidifies as pure silicon forming acicular shaped plates, the aluminum forms the matrix surrounding the silicon. Some of the aluminum may combine with silicon and other metals such as iron (Fe), and manganese (Mn), to form Chinese script.

One way to modify the silicon eutectic phase of Al-Si alloys is to employ a "chemical" modification, by adding a small amount of strontium or sodium. Another way is to employ a "thermal" modification, by subjecting castings to heat treatment (10).

Regarding chemical modification, in 2003 Frederick Shleg mentioned that: "The silicon plates decrease the ductility of the Al-Si alloys. In order to change the size and shape of the silicon plates in the Al-Si alloys, modifiers can be added to the alloy. Among

the modifiers are sodium (Na), strontium (Sr), calcium and antimony. Of these modifiers, Na addition is accompanied by a violent reaction, which itself causes severe agitation and can result in hydrogen pickup. Strontium does not react violently and has high recovery (about 90%), reasons by which it is the most popular modifier in the United States and Canada (11).

In order to properly evaluate the efficiency of modification, it is important to determine and rate the microstructure. Gruzleski and Closset showed how the modification rating can be evaluated by examining a polished section under a microscope and assigning to each class the proportion of the sample surface which has a particular type of modification (12). For example, suppose a given sample contains roughly 20% class 3, 50% class 4 and 30% class 5. Its modification rating would be calculated as:

$$M.R.= (0.2 \text{x} 3)+(0.5 \text{x} 4)+(0.3 \text{x} 5)=4.1$$

The main effect of chemical modification is on the microstructure, and it is this microstructural change which influences directly the mechanical properties. The coarse silicon plates of the unmodified acicular silicon structure act as internal stress raisers in the microstructure and provide easy paths for fracture. With modification, the structure becomes finer and the silicon more rounded, and modified structures display somewhat higher tensile properties and appreciably improved ductility when compared to similar but unmodified structures (13).

In addition to the eutectic silicon shape and size, the dendrite arm spacing (DAS) determined by the cooling rate through the mushy zone is of prime importance. Thus, as aluminum alloys solidify, dendrites form and faster cooling rates result in smaller values

of DAS cells. The closer the dendrites are to one another, the more improved the mechanicals properties (i.e., UTS and elongation) will be. A means of measuring the distance between these dendrites has been developed and can be used for estimating the mechanical properties of the aluminum alloy upon solidification (14).

At this point it is very important to separate two concepts that are wrongly interrelated, the grain size and the DAS. As Frederick Shleg established, the DAS, which is not related in any direct way to the grain size, can be varied considerably by cooling rate and by choice of casting method (15). Smaller DAS values are caused by faster solidification rates, which are usually associated with finer as-cast grain sizes, but it is the DAS and not the grain size which is the determining factor in the mechanical properties.

Another important parameter of quality in castings is porosity, which is the most common defect found in cast metals, and is the major cause of rejection of castings. Some effects of porosity on properties of the cast structure are: decreased tensile and elongation properties, low surface appearance, low fatigue and impact properties. The impact of internal porosity on properties is caused by the reduction in effective area by pore volume fraction, and by stress concentrations at voids leading to premature failure. Porosity in aluminum is caused by the precipitation of hydrogen from liquid solution or by shrinkage during solidification, and more typically by a combination of these effects. However, the most common cause of hydrogen introduced into the molten metal comes from dissociation of water vapor at the surface of the liquid aluminum. The chemical equation to explain this phenomenon is presented next (16):

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H$$
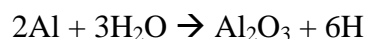
Such porosity occurs in the very last liquid regions to freeze, and both shrinkage and dissolved hydrogen are necessary for its formation because of the extreme difficulty of nucleating a pore in a solidifying metal system. In conclusion, hydrogen is the gas most frequently precipitated as a single element and it shows appreciable solubility in most casting alloys, which leads to the removal of the dissolved hydrogen in the molten aluminum alloy in order to produce high quality castings (17).

The present study was designed as a test of the effect of chemical and thermal modification of A356.0 aluminum alloy on the life of a cutting tool. If strontium modifies the silicon from an acicular to a fibrous microstructure, as the literature suggests, then it is expected to contribute to reduced wear on the cutting tool, and as a consequence, result in a higher number of drilled holes prior to tool failure than that experienced in an unmodified, as-cast condition.

Another technique to successfully modify the silicon phase of Al-Si alloys is heat treatment. Heat treatment refers to any of the heating and cooling operations that are performed for the purpose of changing the mechanical properties, the metallurgical structure, or the residual stresses of a metal product (18). Heat treatment enables the development of a desired balance of properties required for consistent service performance (19). Commonly, aluminum castings are heat treated for homogenization, and stress relief, but for this study the main purpose of heat treatment is to optimize strength, ductility, and machinability. The heat treatment most commonly used to increase the strength of aluminum alloys is a three step process: solution heat treatment (dissolution of soluble phases), quenching (development of supersaturation), and age hardening (natural or artificial aging). Solution treatments consist of soaking the alloy at

a temperature sufficiently high and for a time long enough to achieve a nearly homogeneous solid solution (20). Quenching after solution treatment, refers to the process whereby aluminum alloy components must be cooled, usually at room temperature. This is a straightforward operation, since the aim is to achieve a maximum supersaturation of alloying elements in preparation for subsequent ageing (21). After solution treatment and quenching, hardening is achieved either at room temperature (natural aging) or with a precipitation heat treatment (artificial aging).

In addition, to specify the mechanical properties of an alloy and the way in which these properties were achieved, a system of temper nomenclature has also been adopted as part of the Interactive Authoring and Display System (IADS). Particularly, in this study, a T6 heat treatment program was used, which denotes solution treatment, quenching, and artificial ageing.

Handbooks offer typical heat treatment values for aluminum alloy casting (sand and permanent-mold). So, given an A356 alloy sand mold casting, it is recommended to use 540 ºC (1000 ºF) for 6-12 hours for the solution heat treatment, room temperature water for quenching, and 155 ºC (310 ºF) for 2-5 hours for aging treatment (22).

During the heat treatment process, the once needle-type silicon particles in Al-Si alloys change to a sphere-like shape as a result of a resistance of these particles to release energy when they are put under high temperatures. This fragmentation and rounding of originally sharp silicon platelets is the most accepted mechanism to explain the modification that takes place in Al-Si eutectics (23).

Therefore, it was expected that if silicon particles presented a rounded morphology rather than needle-type platelets, then reduced wear on the cutting tool would be clearly evident, again, resulting in a higher number of drilled holes prior to tool failure.

This study evaluated three different conditions of A356 alloy, as-cast (i.e., unmodified), strontium modified, and Sr modified plus T6 heat treatment. The addition of strontium during the melting process and the heat treatment applied to aluminum castings are respectively considered chemical and thermal modifiers of the silicon phase contained within the aluminum. These chemical and thermal modifications to the silicon phase were expected to exert influence on tool wear and to result in a significant increase in the number of holes drilled prior to tool failure.

Other parameters of the microstructure of the Al-Si alloy, such as the dendrite arm spacing and porosity, were calculated and evaluated during the study, but these were assumed to remain constant, since their variations among all samples were not expected to be significant (less than 5%). These irrelevant variations are due to the fact that modifiers of these parameters, such as chills for the DAS, were not used. Regarding porosity control, the same level of degassing with nitrogen was used for all samples, which would result in homogeneous levels of porosity among samples. This rationale explains why these data were not contemplated in the tool wearing analysis and why they were evaluated and presented just for characterization purposes.

An accutorque wireless sensor captured the torques and thrusts generated when machining the aluminum plates. Using a Lab View application, peak values of these

variables were measured and recorded. This information was used to support the results

obtained from the analysis of mechanical properties, such as UTS and elongation. As

more wear occurred in the drill, it was expected that more torque and thrust would be

observed at the spindle.

II. METHODOLOGY

Specimen

The available specimens were comprised of 20 A356 aluminum alloy plates whose

dimensions were 8''x8''x1''. Of these 20 Al plates, 5 remained in as-cast condition, 7

plates were strontium modified, and 8 plates were strontium modified and T6 heat treated.

The aluminum used to make these plates was a combination of 50% pure and 50% recycled

aluminum provided by Texas State.

Moreover, 18 tension bars were poured, in order to properly analyze the tensile

properties of each condition: 6 bars remained in as-cast condition, 6 were strontium

modified, and 6 were strontium modified and T6 heat treated.

The cutting tools used for the drilling were ¼" diameter high speed steel (HSS) twist

drills manufactured by Hitachi Koki USA, Ltd. Table 1 lists the characteristic features of the

tool geometry. Three drills were randomly assigned to each category of modification

condition (i.e., three drills to the as-cast condition, three drills to the Sr. modified condition

and three drills to the Sr. modifies plus heat treatment condition) making a total of 9 drill bits

across the entire experimental design.

Table 1. Characteristics of the Tool Geometry

Characteristic	Detail
Drill Diameter	1/4" in.
Drill Type	2-flute, high helix
Point Angle	118º
Shank Type	Cylindrical
Overall Length	3.93 in.

Procedures

Groups of aluminum plates of three conditions, as-cast, strontium modified and strontium modified plus heat treatment were drilled to observe, measure, and analyze the effects that different microstructures have on the cutting tool. In order to evaluate the behavior and efficiency of the cutting tool when it drilled a particular number of holes (i.e., average of the first ten holes, 31st through 40th hole, and 61st through 70th hole drilled by each individual drill bit), a magnetic wireless sensor was attached to the milling machine to measure the torque and thrust applied to the spindle.

Two experimental designs were carried out in this study. The first experimental design incorporated one dependent variable, the number of holes achieved with each drill prior to tool failure, and one independent variable, the microstructural condition of the aluminum plates (i.e. as-cast, strontium modified, and strontium modified plus heat treatment). Three drill bits were randomly assigned to each of the three experimental conditions. This design can be classified as a fully randomized one-dimension design. Figure 2 illustrates the organization of the design.

Condition of A356 Castings		
As-Cast	Strontium Modified	Sr. Modified plus HT
Number	of drilled	holes

Figure 2. One-dimension Fully Randomized Experimental Design.

The second experimental design can be classified as a 3x3 repeated measures factorial design having level of microstructural modification as one dimension of the

design and progression of the drilling operation as the other dimension. Level of microstructural modification existed at the three levels already mentioned, as-cast, Sr modified, and Sr. modified plus heat treatment. Progression of the drilling operation also existed at three levels, average of the ten first holes, 31st through 40th hole, and 61st through 70th hole. These specific sequential holes were theoretically important because they permitted to compare peak torque and peak thrust among the experimental conditions even when the number of achieved was not the same for the three conditions. As discussed above, three drill bits were randomly assigned to each of the levels of microstructural modification. Microstructural modification, then, would be considered a between-specimen effect. Repeated measurements were taken of peak torque and thrust for each of the drill bits assigned to the levels of microstructural modification. Accordingly, progression of the drilling operation would be considered a within-specimen effect. Figure 3 illustrates the organization and structure of this experimental design.

Progression of Drilling Operation
(A Within-Specimen Effect)

	1st Hole	35th Hole	70th Hole
As-Cast	n=3	Drill Bits	Per Row
Sr Modified	Peak	Values of	Torque
Sr Mod + HT		and Thrust	

Modification Condition (A Between-Specimen Effect)

Figure 3. A 3x3 Repeated Measures Factorial Design for the Dependent Variables of

Peak Torque and Peak Thrust.

In order to clearly and properly describe each step of the study, the three different conditions of the A356 castings will be separately explained.

1. - As-Cast condition.

First, silica sand molds for the aluminum plates and the tensile samples were made using the Air-Set mold maker (see Figure 4). Then, an induction furnace (see Figure 5) was used to heat and melt the aluminum contained in the crucible inside the furnace.
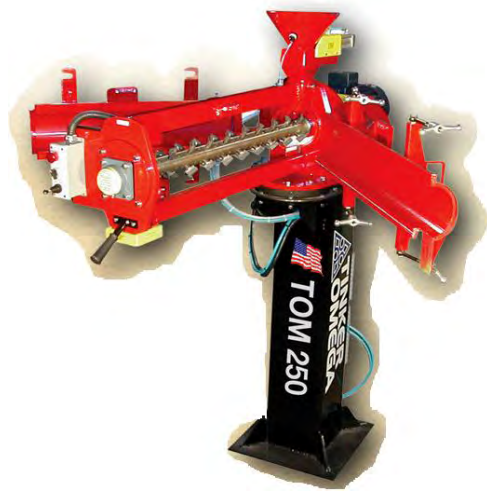
Figure 4. Air-Set Silica Sand Mold Maker.   Figure 5. Removable Crucible Furnace.

A thermocouple was used to constantly measure the temperature until it reached 1310 ºF ± 10 ºF. At this temperature, a degassing process was conducted using a degasser bell (see Figure 6) which injected nitrogen (N_2) to the melt for 15 minutes to avoid porosity in the casting. The purpose of introducing N_2 is that it disperses the hydrogen contained in the molten aluminum more evenly by moving the H_2 from an area of high pressure (in the melt) to an area of low pressure (the inert gas).

Figure 6. Degasser Bell.

Once the degassing was completed, one sample was taken using a crucible of 150 grams and analyzed in the reduced pressure tester (see Figure 7). After comparing the degassed sample with a gas sample chart that provides standard levels of porosity recommended by the American Foundry Society (see Figure 8), 5 aluminum plates and 6 tensile samples were poured.

Figure 7. Reduced Pressure Tester.

A milling machine (see Figure 9) was operated with a ¼'' HSS drill to make a series of through holes in each of the aluminum plates. Each drill was used until it could not perform its task properly, which is to say that the drill was no longer able to completely perforate the plate. Three completely new drills were used following the same

pattern of operation. A description of the center-to-center spacing of this pattern is better explained in Figure 10. After each drill failed, the number of holes made was observed and properly recorded.

Figure 8. Aluminum Comparative Standards for Gas (100 mm pressure).

Figure 9. Milling Machine.   Figure 10. Pattern of the Drilled Holes.
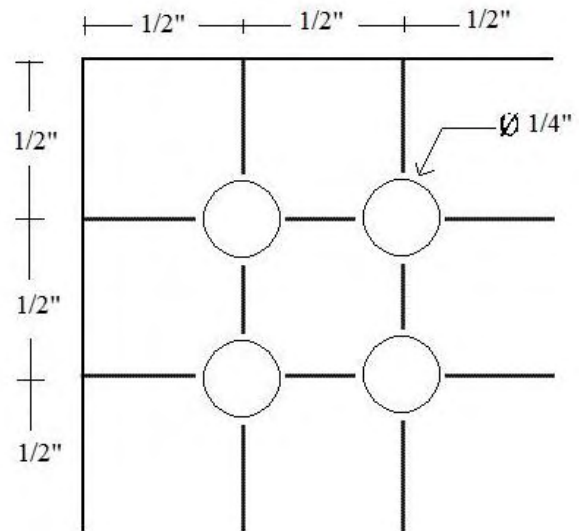
Attached at the spindle of the milling machine was a magnetic wireless sensor
(see Figure 12) that measured the torque and thrust applied to make each hole. As the tool
repeatedly drilled into the aluminum plate its edges and point progressively became
worn, which resulted in an inefficient machining operation represented by elevated torque
and thrust levels. These levels were expected to increase dramatically as the tool
approached its point of failure. Thus, torque and thrust are useful parameters to evaluate
the condition of the tool. The sensor sent the information to an amplifier, which was
connected to a computer that in turn was running a Lab View application for display and
recording of the data (see Figure 11). Lab View was used not only to graphically evaluate
the torque and thrust levels, but to build a database with the peak values of these
variables for each hole.

Figure 11. Schematic Diagram Showing the Experimental Set-up. Figure 12. Accutorque Sensor.

A metallographic analysis was conducted using three specimen of aluminum, which were cut from the cast plates. Each specimen was a 1"x 1" x 1" cube of aluminum cut from the plate, which contained the hole. Since the metallographic microscope requires polished sections to show clear and consistent images, each cube had to be cut in half and just one half polished in its sectioned face (see Figure 13) using the metallographic preparation equipment (see Figure 14).
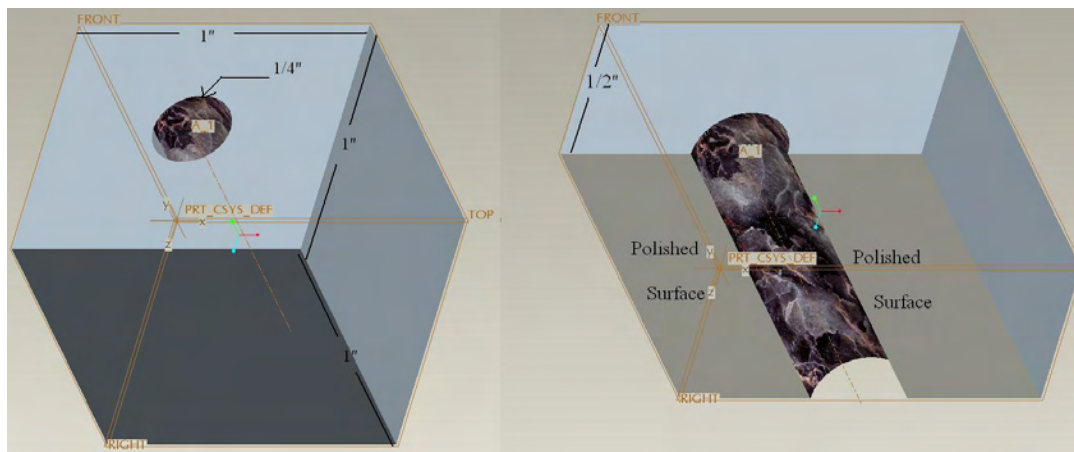
Figure 13. Aluminum Cube Cut From the Plate and The Surface to be Polished.

Figure 14. Metallographic Preparation Equipment.

The metallographic microscope allowed the analysis of three important microstructural characteristics in the samples collected, such as modification rating (MR), dendrite arm spacing (DAS), and porosity. The modification rating was determined by comparing the silicon phase morphology immersed in the aluminum matrix, as observed in the microscope, with the microstructure control chart for hypoeutectic Al-Si alloys offered by the AFS (see Figure 15). Since no modification of any type (thermal or chemical) was applied to the as-cast condition, the lowest level depicted in the AFS's chart was expected, which is represented by large-needle-type silicon plates (i.e., modification class 1, fully unmodified structure).

In order to obtain a representative DAS value for this condition, one photograph was taken for every analyzed hole. Then, the total distance, in micro-meters, between 10 dendrite arms was measured and this sum divided by the number of dendrites (i.e., divided by 10) (see Formula 1). In the as-cast condition 3 holes were analyzed. The final DAS value was the average of these three calculated values.

$$DAS = \frac{dis\tan ce[\mu m]}{10}$$

Formula 1. DAS Calculation.

Regarding porosity, one photograph at low magnification scale was taken for each of the three specimen cut from the cast plates. Then a transparency film with a 50 x 50 matrix printed on it was overlapped onto the low magnification photograph. The size of the matrix and the photograph were the same (i.e., 6.75 in x 5.3 in). In this way, the number of pores per unit area was calculated per photograph (i.e., percentage of pores per area) and a final average value from the three pictures was obtained.

Mechanical properties such as the UTS and elongation were obtained by analyzing the tensile samples in the Tinius Olsen testing machine. These data were correlated with the peak values of torque and thrust obtained for each analyzed hole in order to more confidently establish the linkage among microstructural characterization (i.e., unmodified vs. modified), mechanical properties, and tool life. Since it was believed that a dull tool would result in higher values of torque and thrust at the spindle, it was further believed that the as-cast condition would exhibit the poorest mechanical properties, and thus, the highest peak values of torque and thrust (see Table 2). By contrast, it was believed that the Sr. modified plus heat treatment condition would exhibit the best mechanical properties combined with the lowest peak values of torque and thrust. It was further believed that the Sr. modified condition would yield intermediate mechanical properties combined with intermediate values of torque and thrust.

Figure 15. Microstructure Control in Hypoeutectic Al-Si Alloys Chart. AFS Inc, 1986.

Table 2. Expected Outcomes for Each Alloy Condition

Alloy Condition	Mechanical Properties		Forces		Dependent Var.
	Ultimate Tensile Strenght (MPa)	Elongation (%)	Peak Torque (Nm)	Peak Thrust (Nm)	Number of drilled holes
As-Cast	Low	Low	High	High	Low
Strontium Mod.	Medium	Medium	Medium	Medium	Medium
Strontium Mod. Plus HT	High	High	Low	Low	High

The experimental sequence is presented in Table 3 with a description of the equipment used, as well as a summary of important details associated with each step.

Table 3. Experimental Sequence for the As-Cast Condition

As cast condition			
Step	Process	Equipment	Details
1	Melting	Induction Furnace	1310ºF ± 10 ºF
2	Verify Temperature	Thermo couple K-type	
3	Taking samples	Crucible	150 gr. Approx
4	Chemical Analysis	Emission spectroscopy	Checking A356 composition and Sr content
5	Degassing	Degasser bell	Using N2 during 10min
6	Verify Temperature	Thermo couple K-type	
7	Pouring	Manual	5 plates and 6 tensile samples
8	Drilling operation	Milling machine	¼'' drill diameter and 1'' deep.
9	Preparation of samples	Metallographic preparation equipment	240, 320, 400, 600 grit.
10	Metallographic analysis	Metallographic microscope	DAS, M.R., and porosity
11	Tensile Analysis	Tinius Olsen Testing Machine	Mechanical properties (UTS, YS, and E)

2. – Strontium Modified condition.

First, silica sand molds for the aluminum plates and the tensile samples were made using the Air-Set mold maker (see Figure 4). Then, an induction furnace (see Figure 5) was used to heat and melt the aluminum contained in the crucible inside the furnace. A thermocouple was used to constantly measure the temperature until it reached 1310 ºF ± 10 ºF.

At this temperature, 40 grams of Al-10%Sr was introduced to the melt to chemically modify the silicon particles. The goal was to introduce between 120 and 140 parts per million of Sr to the melt, and because the crucible in the furnace has a capacity of 33.40 Kg, it was calculated that 40 grams of Sr was enough to obtain a value within the range required. The strontium added to the melt had the purpose of modifying the microstructure of the aluminum plates by changing the morphology of the needle-like silicon particles to a finer and more rounded shape. This change in morphology was expected to result in an increased number of holes drilled prior to drill failure.

Then a degassing process was conducted using a degasser bell (see Figure 6) which injected nitrogen (N_2) to the melt for 15 minutes to avoid porosity in the casting. The purpose of introducing N_2 is that it disperses the hydrogen contained in the molten aluminum more evenly by moving the H_2 from an area of high pressure (in the melt) to an area of low pressure (the inert gas). Once the degassing was completed, one sample was taken using a crucible of 150 grams and analyzed in the reduced pressure tester (see Figure 7). After comparing the degassed sample with a gas sample chart that provides

standard levels of porosity recommended by the American Foundry Society (see Figure 8), 7 aluminum plates and 6 tensile samples were poured.

A milling machine (see Figure 9) was operated with a ¼'' HSS drill to make a series of through holes in each of the aluminum plates. Each drill was used until it could not perform its task properly, which is to say that the drill was no longer able to completely perforate the plate. Three completely new drills were used following the same pattern of operation. A description of the center-to-center spacing of this pattern is better explained in Figure 10. After each drill failed, the number of holes made was observed and properly recorded. Attached at the spindle of the milling machine was a magnetic wireless sensor (see Figure 12) that measured the torque and thrust applied to make each hole. As the tool repeatedly drilled into the aluminum plate its edges and point progressively became worn, which resulted in an inefficient machining operation, represented by elevated torque and thrust levels. These levels were expected to increase dramatically as the tool approached to its point of failure. Thus, torque and thrust are useful parameters to evaluate the condition of the tool. The sensor sent the information to an amplifier, which was connected to a computer that in turn was running a Lab View application for display and recording of the data (see Figure 11). Lab View was used not only to graphically evaluate the torque and thrust levels, but to build a database with the peak values of these variables for each hole.

A metallographic analysis was conducted using three specimen of aluminum, which were cut from the cast plates. Each specimen was a 1"x 1" x 1" cube of aluminum cut from the plate, which contained the hole. Since the metallographic microscope

requires polished sections to show clear and consistent images, each cube had to be cut in half and just one half polished in its sectioned face (see Figure 13) using the metallographic preparation equipment (see Figure 14).

The metallographic microscope allowed the analysis of three important microstructural characteristics in the samples collected, such as modification rating (MR), dendrite arm spacing (DAS), and porosity. The modification rating was determined by comparing the silicon phase morphology immersed in the aluminum matrix, as observed in the microscope, with the microstructure control chart for hypoeutectic Al-Si alloys offered by the AFS (see Figure 15). Since strontium addition to the melt (chemical modification) was applied to this condition, a medium level of modification depicted in the AFS's chart was expected, which is represented by partially modified silicon plates (i.e., modification class 3 or 4, absence of lamellar structure).

In order to obtain a representative DAS value for this condition, one photograph was taken for every analyzed hole. Then, the total distance, in micro-meters, between 10 dendrite arms was measured and this sum divided by the number of dendrites (i.e., divided by 10) (see Formula 1). In the Sr. modified condition 3 holes were analyzed. The final DAS value was the average of these three calculated values.

Regarding porosity, one photograph at low magnification scale was taken for each of the three specimen cut from the cast plates. Then a transparency film with a 50 x 50 matrix printed on it was overlapped onto the low magnification photograph. The size of the matrix and the photograph were the same (i.e., 6.75 in x 5.3 in). In this way, the

number of pores per unit area was calculated per photograph (i.e., percentage of pores per area) and a final average value from the three pictures was obtained.

Mechanical properties such as the UTS and elongation were obtained by analyzing the tensile samples in the Tinius Olsen testing machine. These data were correlated with the peak values of torque and thrust obtained for each analyzed hole in order to more confidently establish the linkage among microstructural characterization (i.e., unmodified vs. modified), mechanical properties, and tool life. Since it was believed that a dull tool would result in higher values of torque and thrust at the spindle, it was further believed that the as-cast condition would exhibit the poorest mechanical properties, and thus, the highest peak values of torque and thrust (see Table 2). By contrast, it was believed that the Sr. modified plus heat treatment condition would exhibit the best mechanical properties combined with the lowest peak values of torque and thrust. It was further believed that the Sr. modified condition would yield intermediate mechanical properties combined with intermediate values of torque and thrust.

The experimental sequence is presented in Table 4 with a description of the equipment used, as well as a summary of important details associated with each step.

Table 4. Experimental Sequence For the as Strontium Modified Condition

Strontium modified condition			
Step	Process	Equipment	Details
1	Melting	Induction Furnace	1310ºF ± 10 ºF
2	Verify Temperature	Thermo couple K-type	
3	Adding Sr to the melt	Manual	Target: 120ppm - 140 ppm. 40 gr of Al-10%Sr approx.
4	Taking samples	Crucible	150 gr. Approx
5	Chemical Analysis	Emission spectroscopy	Checking A356 composition and Sr content
6	Degassing	Degasser bell	Using N2 during 10min
7	Verify Temperature	Thermo couple K-type	
8	Pouring	Manual	7 plates and 6 tensile samples.
9	Drilling operation	Milling machine	¼'' drill diameter and 1' deep.
10	Preparation of samples	Metallographic preparation equipment	240, 320, 400, 600 grit.
11	Metallographic analysis	Metallographic microscope	DAS, M.R., and porosity
12	Tensile Analysis	Tinius Olsen Testing Machine	Mechanical properties (UTS, YS, and E)

3. - Modified and heat treated condition.-

First, silica sand molds for the aluminum plates and the tensile probes were made using the Air-Set mold maker (see Figure 4). Then, an induction furnace (see Figure 5) was used to heat and melt the aluminum contained in the crucible inside the furnace. A thermocouple was used to constantly measure the temperature until it reached 1310 ºF ± 10 ºF.

At this temperature, 40 grams of Al-10%Sr was introduced to the melt to chemically modify the silicon particles. The goal was to introduce between 120 and 140 parts per million of Sr to the melt and because the crucible in the furnace has a capacity of 33.40 Kg, it was calculated that 40 grams of Sr was enough to obtain a value within the range required. The strontium added to the melt had the purpose to modify the microstructure of the aluminum plates by changing the morphology of the needle-like silicon particles to a finer and more rounded shape. This change in morphology was expected to improve the surface finish and result in an increase number of holes drilled prior to drill failure.

Then a degassing process was conducted using a degasser bell (see Figure 6) which injected nitrogen (N_2) to the melt for 15 minutes to avoid porosity in the casting. The purpose of introducing N_2 is that it disperses the hydrogen contained in the molten aluminum more evenly by moving the H_2 from an area of high pressure (in the melt) to an area of low pressure (the inert gas). Once the degassing was completed, one sample was taken using a crucible of 150 grams and analyzed in the reduced pressure tester (see Figure 7). After comparing the degassed sample with a gas sample chart that provides standard levels of porosity recommended by the American Foundry Society (see Figure 8), 8 aluminum plates and 6 tensile samples were poured.

All 8 plates and tensile samples were put under a carefully controlled heat treatment process. First, a solution treatment was provided in the heat treatment oven (see Figure 16) at 540 ºC for 4 hours. Immediately after, all the pieces were quenched in water at room temperature. Finally, the pieces returned to the oven for an artificial aging at a

temperature of 155 ºC for 3 hours. Once the heat treatment process was completed, the once needle-type silicon particles were expected to change to a sphere-like shape which would cause a fragmentation and rounding of originally sharp silicon platelets improving both tool life and the surface finish of the drilled holes.

Figure 16. Heat Treatment Oven.

A milling machine (see Figure 9) was operated with a ¼'' drill to make a series of through holes in each of the aluminum plates. Each drill was used until it could not perform its task properly, which is to say that the drill was no longer able to completely perforate the plate. Three completely new drills were used following the same pattern of operation. A description of the center-to-center spacing of this pattern is better explained in Figure 10. After each drill failed, the number of holes made was observed and properly recorded. Attached at the spindle of the milling machine was a magnetic wireless sensor (see Figure 12) that measured the torque and thrust applied to make each hole. As the tool repeatedly drilled into the aluminum plate its edges and point progressively became worn, which resulted in an inefficient machining operation represented by elevated torque and thrust levels. These levels were expected to increase dramatically as the tool

approached its point of failure. Thus, torque and thrust are useful parameters to evaluate the condition of the tool. The sensor sent the information to an amplifier, which was connected to a computer that in turn was running a Lab View application for display and recording of the data (see Figure 11). Lab View was used not only to graphically evaluate the torque and thrust levels, but to build a database with the peak values of these variables for each hole.

A metallographic analysis was conducted using three specimens of aluminum, which were cut from the cast plates. Each specimen was a 1"x 1" x 1" cube of aluminum cut from the plate, which contained the hole. Since the metallographic microscope requires polished sections to show clear and consistent images, each cube had to be cut in half and just one half polished in its sectioned face (see Figure 13) using the metallographic preparation equipment (see Figure 14).

The metallographic microscope allowed the analysis of three important microstructural characteristics in the samples collected, such as modification rating (MR), dendrite arm spacing (DAS), and porosity. The modification rating was determined by comparing the silicon phase morphology immersed in the aluminum matrix, as observed in the microscope, with the microstructure control chart for hypoeutectic Al-Si alloys offered by the AFS (see Figure 15). Since strontium addition and heat treatment (chemical and thermal modification) were applied to this condition, the highest level of modification depicted in the AFS's chart was expected, which is represented by a fibrous silicon eutectic (i.e., modification class 5 or 6, very fine structure).

In order to obtain a representative DAS value for this condition, one photograph was taken for every analyzed hole. Then, the total distance, in micro-meters, between 10 dendrite arms was measured and this sum divided by the number of dendrites (i.e., divided by 10) (see Formula 1). In the Sr. modified plus heat treatment condition 3 holes were analyzed. The final DAS value was the average of these three calculated values.

Regarding porosity, one photograph at low magnification scale was taken for each of the three specimen cut from the cast plates. Then a transparency film with a 50 x 50 matrix printed on it was overlapped onto the low magnification photograph. The size of the matrix and the photograph were the same (i.e., 6.75 in x 5.3 in). In this way, the number of pores per unit area was calculated per photograph (i.e., percentage of pores per area) and a final average value from the three pictures was obtained.

Mechanical properties such as the ultimate tensile strength, yield strength, and elongation were obtained by analyzing the tensile samples in the Tinius Olsen testing machine. These data were correlated with the peak values of torque and thrust obtained for each analyzed hole in order to more confidently establish the linkage among microstructural characterization (i.e., unmodified vs. modified), mechanical properties, and tool life. Since it was believed that a dull tool would result in higher values of torque and thrust at the spindle, it was further believed that the as-cast condition would exhibit the poorest mechanical properties, and thus, the highest peak values of torque and thrust (see Table 2). By contrast, it was believed that the Sr. modified plus heat treatment condition would exhibit the best mechanical properties combined with the lowest peak values of torque and thrust. It was further believed that the Sr. modified condition would

yield intermediate mechanical properties combined with intermediate values of torque and thrust.

The experimental sequence is presented in Table 5 with a description of the equipment used, as well as a summary of important details associated with each step.

Table 5. Strontium Modified Plus Heat Treatment Condition

Strontium modified plus heat treatment condition			
Step	Process	Equipment	Details
1	Melting	Induction Furnace	1310ºF ± 10 ºF
2	Verify Temperature	Thermo couple K-type	
3	Adding Sr to the melt	Manual	Target: 120ppm - 140 ppm. 40 gr of Al-10%Sr approx.
4	Taking samples	Crucible	150 gr. Approx.
5	Chemical Analysis	Emission spectroscopy	Checking A356 composition and Sr content
6	Degassing	Degasser bell	Using N2 during 10min
7	Verify Temperature	Thermo couple K-type	
8	Pouring	Manual	8 plates and 6 tensile samples.
9	Heat treatment	Heat treatment oven	520 ºC (968 ºF) for 4 hrs
10	Quenching	Manual	Immediately after solution treatment. Water at room temperature
11	Aging	Heat treatment oven	180 ºC(360F) for 3 hrs
12	Drilling operation	Milling machine	¼'' drill dia. and 1' deep.
13	Preparation of samples	Metallographic preparation equipment	240, 320, 400, 600 grit.
14	Metallographic analysis	Metallographic microscope	DAS, M.R., and porosity
15	Tensile Analysis	Tinius Olsen Machine	Mechanical Properties (UTS, YS, and E)

Instrumentation

       Accu-torque Sensor: A non-contact magneto-static torque sensor (see Figure 18)

was mounted on the chuck of the milling machine between the drill tip and the drill motor

to measure the torque generated during drilling. The thrust force acting along the Z

direction of the drill was measured simultaneously by this same sensor. The signals from

the sensor were transmitted to an amplifier and digitalized by an analog to digital

converter using a data acquisition system from which data were transferred to a computer

for analysis (see Figure 17). LabView was the software selected to record the levels of

both thrust and torque.
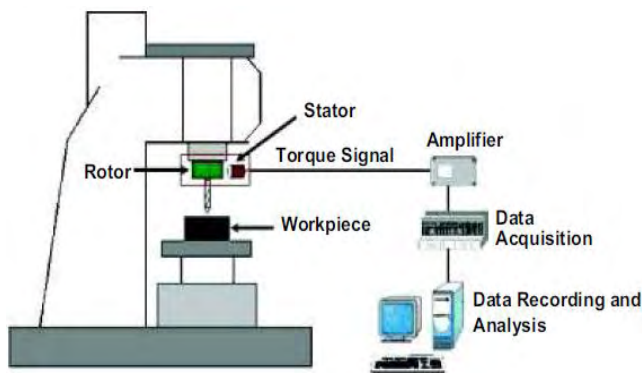
Figure. 17. Schematic Diagram Showing the Experimental Set-up. Figure 18. Accutorque Sensor.

       Metallographic Microscope: Once the samples taken from the aluminum plates

were properly prepared with the metallographic equipment, they were ready to be

analyzed in the Nikon, Epiphot 300 metallographic microscope (see Figure 19). Different

magnification levels allowed for the study of modification rating (200x), dendrite arm

spacing (150x), and porosity (50x) in these samples. This microscope works with the L1

software, which captured the images corresponding to the parameters under study.

Figure 19. Metallographic Microscope.

Tensile Analysis: Tensile samples corresponding to each experimental condition were analyzed in the Tinius Olsen Testing Machine (see Figure 20), in order to establish representative levels of ultimate tensile strength, yield strength, and elongation. The 600kN (120,000 lbf) Super L model features a dual pressure hydraulic loading system and rugged four column construction for exceptional load frame rigidity. The machine has an operating range from 240 lbf to 120,000 lbf and maintains an accuracy of +/- 0.5% of the displayed load across this range. Also, it features a display and a controller, making this system a reliable and robust data acquisition instrument.

Figure 20. Tinius Olsen Testing Machine.

Equipment

Air-Set Tinker Omega, TOM-125 (see Figure 21a): It was used to create the molds (see Figure 21b) for the aluminum plates and tensile samples. This equipment mixes silica sand #79 (i.e., recommended by the AFS, Inc.) and three kind of resins. Two of these resins are binders that in combination allow the adhesion of silica sand grains and the third is an organic based catalyst added in controlled proportions to accelerate the hardening process.
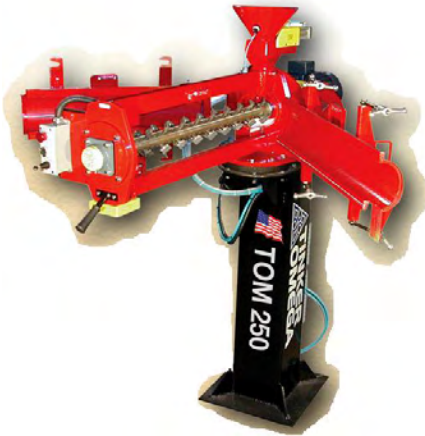
Figure 21a. Air-Set Silica Sand Mold Maker.

Figure 21b. Molds for the Aluminum Plates and Tensile Samples Molds.

Induction Furnace: The aluminum poured into the molds was melted using an Inductotherm VIP furnace and a removable crucible made of SiC (see Figure 22 & 23). This crucible has a volume of 0.011 [m^3] (709.3 in^3) and a capacity of 31 Kg. (68.2 lb). In total, four heats were necessary to pour 20 aluminum plates and 18 tensile samples.

Figure 22. Removable Crucible & Induction Furnace.

Figure 23. Induction Power Supply.

VAC-U-CHEK Reduced Pressure Tester (CMH Manufacturing Co.): This equipment was used to obtain a qualitative assessment of the level of hydrogen dissolved in the molten metal (see Figure 24). A small sample (about 150 grams) of liquid alloy was allowed to solidify under a partial vacuum. Low pressure during solidification accentuates porosity formation, and a qualitative idea of the level of hydrogen present was gained by an examination of the surface of the sample and the appearance of a sectioned specimen.

Figure 24. Reduced Pressure Tester.

Swest Inc. Heat Treatment Oven: This oven has a capacity of 0.1 m^3 (3.9 ft^3) and worked with a controller model No. 160-930 (see Figure 25). Only the plates from the third experimental condition (i.e., strontium modified plus heat treatment) received the heat treatment, which consisted of three steps. First, a solution treatment was provided to the aluminum plates at 540 ºC for 4 hours. Immediately after, all the plates were quenched in water at room temperature and returned to the oven for an artificial aging at a temperature of 155 ºC for 3 hours.

Model:	GL22S
Volts:	240
Phase:	1
Hz:	50
Amp:	25
Max. Temperature:	1700 ºF

Oven Specifications

Figure 25. Heat Treatment Oven.

Milling Machine: All drilling was performed using a Jet milling machine model: JTM-4VS (see Figure 26). Prior to drilling the desired cutting parameters were established, such as speed (2500 RPM or 50 m/min), feed rate (0.25 mm/rev), and depth of hole (1"). While the

linear transverse motion of the machine table in the X and Y directions were manually controlled

by the operator, a feed motion was applied automatically by the milling machine, in the Z

direction, for the drilling operation.

Range of Speeds:	60-4,200 (RPM)
Size of Table:	9" x 49"
Longitudinal Table Travel:	36"
Cross Travel:	12"
Max Weight of Workpiece:	660 lbs.
Motor:	3 HP, 3Ph 230 / 460V Prewired 230V

Milling Machine Specifications

Figure 26. Milling Machine.

Metallographic Preparation Equipment: Before the samples cut from the aluminum plates

could be analyzed in the metallographic microscope, they had to be polished in the

Metaserv hand grinder (see Figure 27a). It uses sandpaper of different abrasive grades,

such as 240 grit, 320 grit, 400 grit, and 600 grit to smooth and polish the surfaces to be

analyzed. The polisher used to give a mirror-like finish surface to the samples was the

Struers, DAP-2, which uses a polycrystalline diamond suspension of 0.05 microns (see

Figure 27b).

Figure 27a. Metaserv Hand Grinder.

Figure 27b. Struers Polisher.

III. ANALYTICAL APPROACH

The main goal of this study was to analyze the life of the cutting tool during the drilling of A356 aluminum casting alloys of different microstructures. In order to obtain this difference in the microstructure, the silicon phase contained in this alloy was manipulated by applying chemical and thermal modifiers to the castings. In this way, three different experimental categories of specimens (aluminum plates) were differentiated from each other in the level of modification of their silicon particles. These categories were: as-cast casting condition (i.e., unmodified), strontium modified casting condition, and strontium modified plus heat treatment casting condition.

Before the drilling tests were conducted, it was anticipated that the least number of holes would be obtained in the as-cast condition, an intermediate number of holes would be obtained in the strontium modified condition, and the highest number of holes would be obtained in the Sr. modified plus heat treatment condition. This belief was supported by the literature, which establishes that the coarse silicon plates of the unmodified acicular silicon structure act as internal stress raisers in the microstructure and provide easy paths for fracture. These large-needle-type silicon particles have very high levels of hardness, which dulls the sharp edges of the cutting tool. With modification, these structures become finer and the silicon more rounded, characteristics which contribute to somewhat higher values of ultimate tensile strength and greatly increased values of elongation. In this condition, the hardness of the silicon particles are

very similar to the ones found in the as-cast condition, but the change in their more

rounded and evenly dispersed morphology contributes to extending the sharpness of the

cutting tool. Furthermore, modification and its influence on the mechanical properties of

the castings, is the variable that should establish the more discernable differences in tool

life among the three conditions.

The ultimate tensile strength, yield strength, and elongation were obtained in

order to correctly characterize the mechanical properties associated with each

experimental condition. Table 6 shows typical values for the mechanical properties for

A356 alloy (24).

Table 6. Minimum Mechanical Properties for Alloy A356 – T6 Castings

Alloy Modification	Ultimate Tensile Strength		Elongation
	MPa	ksi	
Unmodified alloy (As-Cast Condition)	77	11	2%
Partially modified alloy (Strontium Modified Condition)	147	21	4%
Fully modified alloy (Sr. Modified Condition plus H. T.)	188	27	8%

A low level of modification like that expected in the as-cast condition, offers poor

mechanical properties (i.e., elongation and UTS) to the aluminum plates due to the large-

needle-type morphology of the silicon phase. It was expected that as the drill dug into the

material, it would repeatedly strike the large and very hard silicon particles, causing it to

lose its sharpness as the number of drilled holes increased. This dullness and change in the geometry of the cutting tool would cause an inefficient evacuation of the chips through the flutes of the drill, which in turn would require more force to advance the drill and complete a hole. Consequently, high adhesion of the chips to the flutes and the cutting edge of the drill was expected, which would lead to high torque values and the least number of drilled holes among the three experimental conditions.

On the other hand, the Sr modified and heat treated condition was the one that would receive the highest level of modification (i.e., increasing roundness of the silicon particles) and the one that was expected to yield the higher number of drilled holes prior to tool failure, due to its improved mechanical properties. As the drill dug into the aluminum plate, it would encounter a more ductile material (i.e., high elongation and UTS values) with evenly dispersed, small, and rounded silicon particles which would prevent the rapid wearing of the tool helping it to preserve its geometry. In this way, chip evacuation would become more efficient and no adhesion of material to the drill's flutes or cutting edge was expected, which would lead to low torque values.

The strontium modified condition (i.e., partially modified, without heat treatment) was expected to offer intermediate values of mechanical properties (i.e., UTS and elongation) that would generate intermediate values of torque and thrust leading to an intermediate number of drilled holes.

The expected influence of microstructural modification on the mechanical properties of the A356 alloy, which in turn affect the torque and thrust to which the cutting tool is subjected, is presented in Table 7. Once actual values of UTS, percentage

of elongation, peak torque and thrust, and number of drilled holes were collected, these

data were mapped into a format similar to that of Table 7. If the pattern of the relative

magnitudes and direction of relationships predicted in Table 7 hold true among the actual

data, this result would provide support for the theory that modification of the silicon

phase contributes to improved tool life in A356.0 aluminum-silicon alloy.

Analysis of whether or not the level of microstructural modification of the

specimens was the determinant factor influencing the number of drilled holes was

accomplished using a one-way Analysis of Variance (ANOVA).

Table 7. Expected Outcomes for Each Alloy Condition

Alloy Condition	Mechanical Properties		Forces		Dependent Var.
	Ultimate Tensile Strenght (MPa)	Elongation (%)	Peak Torque (Nm)	Peak Thrust (Nm)	Number of drilled holes
As-Cast	Low	Low	High	High	Low
Strontium Mod.	Medium	Medium	Medium	Medium	Medium
Strontium Mod. Plus HT	High	High	Low	Low	High

If this ANOVA yielded a significant value of F, it was still necessary to determine

which of the three experimental conditions was significantly different from which others.

Provided that the ANOVA did result in a statistically significant outcome, orthogonal

contrast test was used to determine the extent and direction of these differences among

the three experimental conditions (i.e., as-cast, strontium modified, and Sr modified plus

heat treatment). If the results of this analysis should indicate that a significantly greater

number of drilled holes occurred in the two modified conditions than in the unmodified

as-cast condition, this result too would provide strong support for the theory that modification of the silicon phase contributes to improved tool life in A356.0 Al-Si alloy.

Analysis of whether or not the level of microstructural modification of the specimens affected the peak values of torque and thrust was accomplished using a two-way factorial ANOVA. Level of modification, that is as-cast, Sr. modified, or Sr. modified plus heat treatment, represented one dimension of the design, while progression of the drilling operation, that is the average of the first ten holes, 31st through 40th hole, and 61st through 70th hole, represented the second dimension. The design can be classified as a 3x3 repeated measures factorial design, where level of microstructural modification was a between-specimen effect, while progression of the drilling operation was a within-specimen effect (see Figure 3 on page 19). Three drill bits were randomly assigned to each of three modification conditions, then repeated measurements of peak torque and thrust were taken for each drill bit for the average of the first ten holes, 31st through 40th, and 61st through 70th hole drilled. These particular sequential holes were selected to properly compare peak torque and thrust among the three levels of microstructural modification even when the number of holes achieved in each level was not the same.

If this analysis yielded significant main effects for either independent variable, it was still necessary to determine which of the levels of the independent variables were significantly different from which others. Provided that the ANOVA did result in statistically significant effects on either independent variable, Orthogonal polynomials (trend analysis) test was used to determine the extent and direction of these differences among the levels.

If the results of this analysis indicate that significantly lower levels of torque and thrust were obtained in the modified conditions than in the unmodified as-cast condition, and if the levels of torque and thrust observed in the average of the 61st through 70th drilled hole is significantly higher than that obtained in the average of the first ten drilled holes, this result would provide further strong support for the theory that modification of the silicon phase contributes to improved tool life in A356.0 aluminum-silicon alloy.

Other parameters of the microstructure of this Al-Si alloy, such as the dendrite arm spacing and porosity, were evaluated and calculated using the metallographic microscope, but only for characterization purposes. It was assumed that these parameters would remain constant, since their variations among all experimental conditions were not expected to be significant. Dendrite arm spacing is affected by a rapid chill of the molten metal, and because all plates were made in the same type of sand molds and cooled at the same rate, no variation among the samples was expected. Porosity formation was also expected to remain constant across all experimental conditions because the same method of degasification was applied to all samples.

IV. RESULTS

All drilling tests were performed using a Jet milling machine at a rotational speed of 2500 RPM using a feed rate of 0.006 in/rev and each hole was 1 inch deep. A total of 959 holes were drilled (for all three conditions) in rows with a horizontal center-to-center spacing of 0.5" between the adjacent rows and a vertical center-to-center spacing of 0.5" between the adjacent columns. Figure 28 shows a typical A356 drilled block.
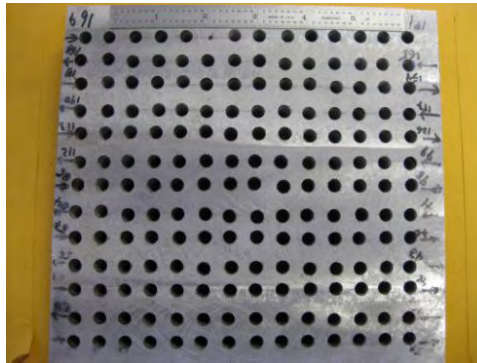
Figure 28. A356 Drilled Aluminum Plate.

Three specimens were cut from the drilled plates corresponding to each condition (i.e., as-cast, Sr. modified, and Sr. modified plus heat treatment) for analysis in the metallographic microscope for the purpose of determining the modification rating, DAS, and porosity for each of these conditions. Table 8 shows means and standard deviations for M. R., DAS, porosity, UTS, and elongation for each microstructural condition.

As established previously, changes in the microstructure of aluminum A356 cast plates were achieved through chemical modification (Sr. modified condition) and thermal modification (Sr. modified plus heat treatment condition).

Descriptive Statistics

Table 8. Descriptive Statistics for Modification Rating, DAS,

Porosity, UTS, and Elongation

		Modification Rating (n=3)	DAS(μm) (n=3)	Porosity[%] (n=3)	UTS(psi) (n=6)	Elongation[%] (n=6)
As-Cast	Mean	2	100.6	2.16	21.520	8.58
	SD	0	16.28	0.13	2.660	1.13
Sr. Modified	Mean	3	85.28	2.92	22.567	9.33
	SD	0	15.95	0.36	1.102	0.89
Sr. Mod. + HT	Mean	4	88.41	1.8	36.780	7.5
	SD	0	13.74	0.21	2.368	0.76
Totals	Mean	3	91.43	2.29	26.956	8.47
	SD	0	8.1	0.57	8.514,7	0.92

Examination of these specimens under the metallographic microscope revealed differences in the aluminum microstructure among all three conditions. The as-cast condition showed a fully unmodified structure where the laminar structure of the large-needle-type silicon particles was evident (see Figure 29a). The partial modification in the Sr. modified condition was differentiated from the as-cast condition by a partial modification of the silicon phase, which was represented by smaller and more rounded silicon particles (see Figure 29b). Finally, the Sr. modified plus heat treatment condition was characterized by an absence of laminar structure, which turned into easily identifiable spherical silicon particles (see Figure 29c). The modification ratings listed in

Figure 29 were determined by comparing these photomicrographs to the AFS chart first

presented in Figure 15 on page 30, and re-presented here for reference.

AFS Chart (M. R.= 1)	Photograph of the As-Cast Condition
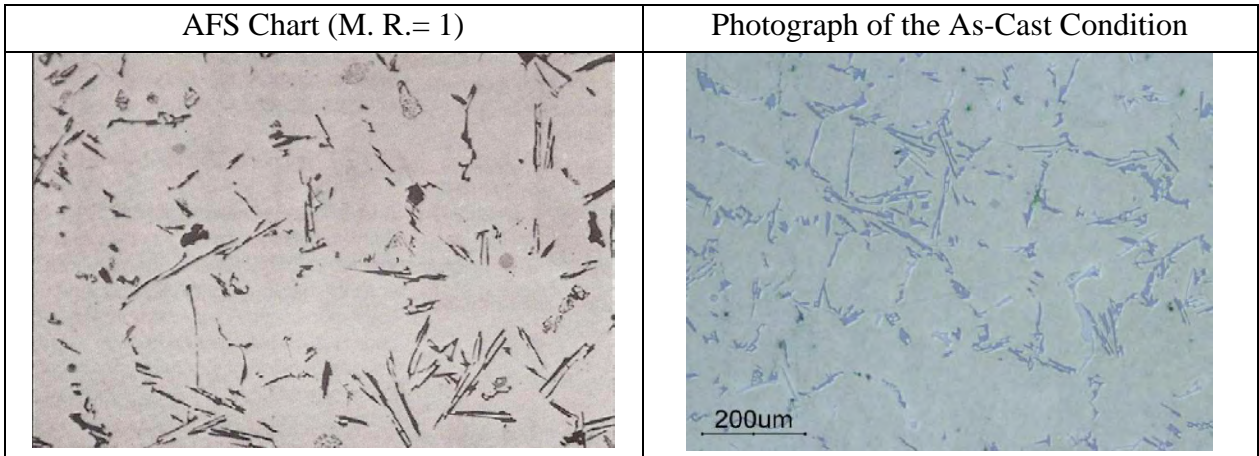
Figure 29a. As-Cast Condition with a M. R. = 1 (Fully Unmodified Structure).

AFS Chart (M. R.= 3)	Photograph of the Sr. Mod. Condition
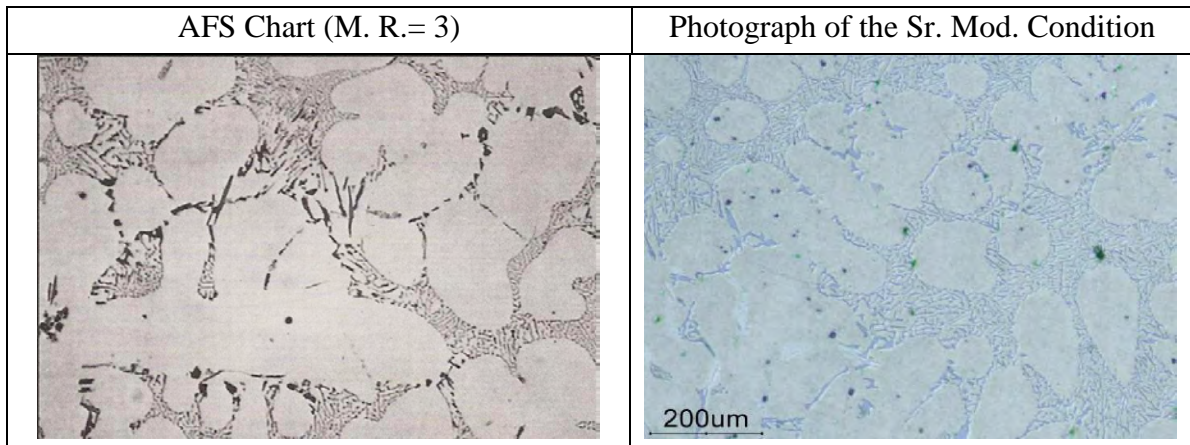
Figure 29b. Strontium Modified Condition with a M. R. = 3 (Laminar Structure).

AFS Chart (M. R.= 4)	Photograph of the Sr. Modified Plus Heat Treatment Condition
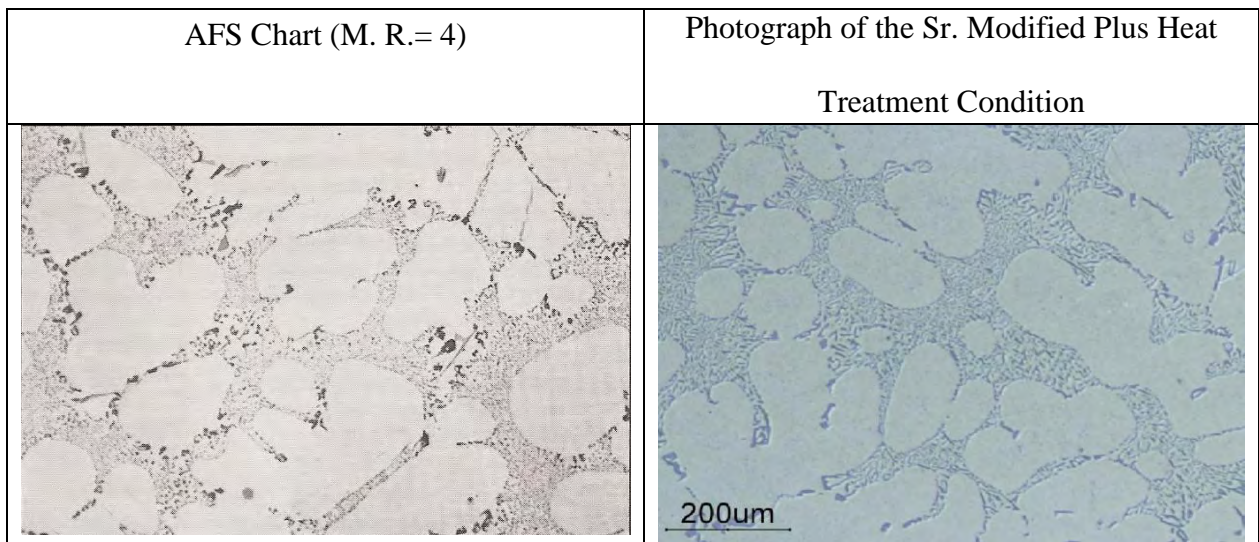
Figure 29c. Sr. Modified Plus Heat Treatment Condition with a M. R. = 4

(Absence of Laminar Structure).

Dendrite arm spacing (DAS) values were expected to remain constant among samples of the three conditions because absolutely all plates were cast in silica sand molds, which offer a low solidification rate of the molten aluminum. All three conditions presented very similar DAS values with the exception of the as-cast condition, but this can be explained by a very difficult dendrite arms identification, which may have caused high misconception of actual dendrite arms size. The reason for this misconception is that dendrite arms found in the as-cast condition are not well defined due to the large and irregular structure of the silicon particles. These silicon particles that surround the dendrite arms do not offer clear boundaries for each arm, which introduces a certain level of uncertainty to the formula used for calculating the DAS. DAS was calculated using the formula first presented on page 29, and re-presented here for reference.

$$DAS = \frac{\text{distance}[\mu m]}{\text{Number of arms}}$$

Formula 1. DAS Calculation.

Porosity remained constant among all aluminum plates as had been anticipated. It is assumed that porosity remained constant across the three conditions of modification because the same method of degasification was used in all three. One photograph at low magnification scale was taken for each of the three specimen cut from the cast plates. Then a transparency film with a 50 x 50 matrix printed on it was overlaid onto the low magnification photograph. The size of the matrix and the photograph were the same (i.e., 6.75 in x 5.3 in). In this way, the number of pores per unit area was calculated per photograph (i.e., percentage of pores per unit area) and a final average value from the three pictures was obtained. The same process was repeated for each microstructural condition.

In addition, six tensile samples per experimental condition were analyzed in the Tinius Olsen machine in order to determine the mechanical properties (i.e., UTS and elongation) for each condition. As expected, UTS and elongation in the Sr. modified condition were higher than in the as-cast condition due to the addition of a chemical modifier (i.e., strontium) during the melting process. Those plates that were chemical and thermal modified (i.e., Sr. modified plus heat treatment condition) showed the highest UTS among the three experimental conditions, but the lowest elongation.

Contrary to what was expected, the as-cast condition resulted in the highest number of drilled holes, followed by the Sr. modified condition and the Sr. modified plus

heat treatment condition. After all drilling had been completed, peak values of torque and thrust were extracted from the database created by LabView and were analyzed to determine the forces acting on the spindle prior to tool failure.

Table 9 shows the means and standard deviations for number of drilled holes, peak torque and peak thrust for each microstructural condition, across three levels of progression of drilling.

Table 9. Descriptive Statistics for Number of Drilled Holes,

Peak Torque, and Peak Thrust

			Progression of Drilling					
			1st-10th Hole		31th-40th Hole		61th-70th Hole	
		Number of Drilled Holes	Torque (Nm)	Thrust (Nm)	Torque (Nm)	Thrust (Nm)	Torque (Nm)	Thrust (Nm)
As-Cast (n=3)	Mean	155	1.44	0.39	1.34	0.40	1.36	0.42
	SD	18.83	0.22	0.02	0.20	0.02	0.25	0.03
Sr. Modified (n=3)	Mean	101	1.33	0.37	1.29	0.42	1.56	0.52
	SD	43.45	0.14	0.02	0.19	0.02	0.29	0.05
Sr. Mod. + HT (n=3)	Mean	63	1.46	0.42	1.38	0.45	1.62	0.52
	SD	13.78	0.2	0.05	0.24	0.03	0.39	0.09
Totals	Mean	106.5	1.41	0.397	1.33	0.426	1.51	0.487
	SD	46.25	0.07	0.02	0.04	0.04	0.14	0.005

Table 10 is presented in order to compare the results obtained in this study with the expected outcomes predicted in Table 6 on page 52. Once actual values of UTS, percentage of elongation, peak torque, peak thrust, and number of drilled holes were collected, these data were mapped into Table 11 for the purpose of making comparisons to the expectations presented in Table 10.

Number of drilled holes for the as-cast and the Sr. modified plus heat treatment condition manifested in the opposite direction to what was expected. Originally it was considered that the as-cast condition would yield the least number of holes and that the Sr. modified plus heat treatment condition would yield the highest number of drilled holes. However, the results showed the highest number of drilled holes in the as-cast condition and the least number of drilled holes in the Sr. modified plus heat treatment condition. The Sr. modified condition resulted as it was expected, that is, yielding an intermediate number of drilled holes.

Peak torque and peak thrust in the as-cast and Sr. modified plus heat treatment conditions also manifested in the opposite direction to what was expected. It was considered that the highest torque and thrust would be generated by the tools used to drill into the as-cast condition and the lowest torque and thrust would be generated by the drills used to cut the Sr. modified plus heat treatment condition. Surprisingly, the cutting tools that drilled into the as-cast condition generated the lowest level of peak thrust and peak torque while the bits used in the Sr. modified plus heat treatment condition generated the highest levels of peak torque and peak thrust. The bits used to drill into the Sr. modified condition showed intermediate levels of peak torque and peak thrust.

Regarding mechanical properties, UTS followed the exact pattern predicted for the three alloy conditions, that is, the lowest UTS for the as-cast condition, medium UTS for the Sr. modified condition, and the highest UTS for the Sr. modified plus heat treatment condition. Elongation in the as-cast and the Sr. modified conditions showed a pattern similar to that expected, but this pattern was opposite expectations for the Sr. modified plus heat treatment condition. It was believed that the Sr. modified plus heat

treatment condition would possess the highest elongation among the three alloy
conditions, but surprisingly it was the one that showed the lowest elongation.

Table 10. Expected Outcomes for Each Alloy Condition

Alloy Condition	Mechanical Properties		Forces		Dependent Var.
	Ultimate Tensile Strength (MPa)	Elongation (%)	Peak Torque (Nm)	Peak Thrust (Nm)	Number of drilled holes
As-Cast	Low	Low	High	High	Low
Strontium Mod.	Medium	Medium	Medium	Medium	Medium
Strontium Mod. Plus HT	High	High	Low	Low	High

Table 11. Actual Outcomes for Each Alloy Condition

Alloy Condition	Mechanical Properties		Forces		Dependent Var.	Hadness
	Ultimate Tensile Strenght (MPa)	Elongation (%)	Peak Torque (Nm)	Peak Thrust (Nm)	Number of drilled holes	Brinell
As-Cast	21.52	8.58	1.38	0.4	155	45
Strontium Mod.	22.567	9.33	1.39	0.44	101	45
Strontium Mod. Plus HT	36.78	7.5	1.49	0.46	63	82

Statistical Analyses

One-way Analysis of Variance (ANOVA)

For each of the experimental conditions, tool life was represented by the number
of drilled holes achieved prior to tool failure, under constant machining conditions. The
as-cast condition manifested the highest number of drilled holes (i.e., 155 holes),
followed by the Sr. modified condition (i.e., 101 holes) and, finally, the Sr. modified plus
heat treatment condition (i.e., 63 holes). Tool life results for the three different

microstructural conditions of A356 castings are presented in Table 8 in terms of the number of drilled holes achieved prior to tool failure.

A one-way Analysis of Variance was performed on number of drilled holes to determine whether or not the level of microstructural modification of the specimens was a determinant factor influencing tool life. The results of this analysis are shown in Table 12. The ANOVA revealed a significant F ratio ($p<0.05$), but the direction of this difference was opposite to what was expected. In addition, Hartley's F_{max} test was performed to determine if the homogeneity of variance assumption could be supported for these data. Hartley's F_{max} statistic is the ratio of the largest cell variance to the smallest:

$$F_{max} = \frac{S^2_{max}}{S^2_{min}} = \frac{43.45^2}{13.78^2} = 9.94$$

Consulting standard tables of Hartley's statistic, the critical value associated with a significance criterion of $p<0.05$ for 3 cells of size 3 is 27.8. Therefore, Hartley's F_{max} was not significant (i.e., $9.94<27.8$), so the homogeneity of variance assumption was supported for these data.

Table 12. One-way Analysis of Variance for Number of Drilled Holes

Source	Df	Sum of Squares	Mean Squeare	F	P
Microstructural Modification	2	12651.55	6325.77	5.2	0.05
Error	6	7298.66	1216.44		
Total	8	19950.21			

It was still necessary to determine which of the three experimental conditions of microstructural modification was significantly different from which others. Orthogonal contrasts were constructed for the purpose of making this determination. The first contrast tested the mean difference between the as-cast condition and a weighted average of both modified conditions (Sr. modified and Sr. modified plus heat treatment). The second contrast tested the mean difference between the Sr. modified condition and the Sr. modified plus heat treatment condition. The first contrast was significant at the $p<0.05$ level and approached significance at $p<0.025$ for 1 and 6 degrees of freedom. The second contrast was not significant.

The sum of squares stemming from the C_{th} contrast is defined as:

$$SSC_c = \frac{n\left(\sum\limits_{j=1}^{q} C_{cj}\, \bar{Y}_{.j}\right)^2}{\sum\limits_{j=1}^{q} C^2_{cj}}$$

Therefore, the sum of squares for the C_1 contrast was:

$$SSC_1 = \frac{3((2)(155) + (-1)(101) + (-1)(63))^2}{2^2 + (-1)^2 + (-1)^2} = 10{,}658$$

The F ratio for the first contrast was:

$$F = \frac{SSC_c/1}{MS_{err}} = \frac{10.658/1}{1216.44} = 8.76$$

Consulting standard tables of the F statistic for 1 and 6 degrees of freedom at $\alpha=0.025$, the critical value of F would be 8.81. Clearly, the first contrast, that is the comparison of

the as-cast condition to a weighted average of both modified conditions, was significant at the conventional level of p<0.05, and it was very nearly significant at p<0.025. From this result, it can be concluded that the as-cast condition yielded a significantly higher number of drilled holes than either modified condition.

The sum of squares for the second contrast was;

$$SSC_2 = \frac{3((0)(155) + (1)(101) + (-1)(63))^2}{0^2 + 1^2 + (-1)^2} = 2,166$$

$$F = \frac{2,166/1}{1,216.44} = 1.78$$

Consulting standard tables of the F statistic for 1 and 6 degrees of freedom at $\alpha=0.05$, the critical value of F would be 5.98. Clearly, the second contrast was not significant. There is no evidence from these data that the two modified conditions differed from one another in the number of drilled holes yielded by each.

Two-way factorial ANOVA

A two-way factorial ANOVA was performed on values of peak torque and thrust to determine whether microstructural modification or progression of drilling affected these dependent variables. Level of modification, that is as-cast, Sr. modified, or Sr. modified plus heat treatment, represented one dimension of the design, while progression of the drilling operation, 1st through 10th hole, 31st through 40th hole, or 61st through 70th hole, represented the second dimension. This particular sequence of holes was compared (in terms of peak torque and thrust) among the as-cast condition, the Sr. modified, and Sr.

modified plus heat treatment conditions. It should be noted that bit #1 in the Sr. modified condition and bits #1 and #3 in the Sr. modified plus heat treatment condition were not able to drill enough holes to be tested in the 61st through 70th range. As a result, bit #1 in the Sr. modified condition had to be evaluated based upon the 55th through 64th hole range, while bits #1 and #3 in the Sr. modified plus heat treatment condition had to be evaluated based upon the 47th through 56th hole range and 43rd through 52nd hole range respectively.

The experimental design can be classified as a 3x3, repeated measures, factorial design, where level of microstructural modification was a between-specimen effect, while progression of the drilling operation was a within-specimen effect. This design was initially presented in Figure 3 on page 19.

Three drill bits were randomly assigned to each of the three modification conditions, and repeated measurements of peak torque and thrust were taken for each drill bit across the levels of progression of drilling, that is, 1st through 10th, 31st through 40th, and 65th through 70th drilled holes (with the exceptions noted above).

Just as homogeneity of variance is an assumption that underlies ordinary factorial analysis of variance, a homogeneity of covariance assumption underlies the analysis of data arising from a repeated measures design. In designs utilizing independent, randomly formed treatment groups, it is safe to assume that the magnitudes of experimental errors will be completely random and unrelated to any treatment effects. In a repeated measures design it is not unlikely that the errors associated with an individual unit of study (i.e. a given drill bit) might be correlated. Box has shown that violation of this equi-covariance

assumption tends to lead to an inflation of type I errors (25). This homogeneity of covariance assumption may be tested directly, or in the alternative, a procedure can be used for testing the relevant hypotheses, which relies upon conservative degrees of freedom to ascertain the critical values of F. The F ratios reported in Tables 12 and 13, were calculated in the usual manner (i.e., by dividing the relevant sums of squares by the customary degrees of freedom), however, when entering standard tables of the F statistic, conservative degrees of freedom were used, in lieu of the usual degrees of freedom, to test for statistical significance. This method, which was originated by Box, leads to a test of significance that is always conservative, even in cases where the homogeneity of covariance assumption cannot be supported by the data (25). Of all the hypotheses tests presented in Tables 12 and 13, only the main effect for progression of drilling was significant, and only on thrust. This effect proved to be significant (p<.01) when tested against both the usual and the conservative degrees of freedom. All of the remaining effects, for both torque and thrust, were non-significant when tested against both the usual and the conservative degrees of freedom. Consequently, because all hypothesis tests were in agreement using both sets of degrees of freedom, there was no necessity to test the homogeneity of covariance assumption directly.

The ANOVA for torque is presented in Table 13. Neither main effect, microstructural modification nor progression of drilling was significant at conventional levels. The interaction of progression of drilling with microstructural modification was likewise non-significant. Consequently, no further analysis was called for.

Table 13. Two-way Factorial Analysis of Variance for Torque

Source	Usual Df	Conservative Df	Sum of Squeares	Mean Squeare	F	P
Among Specimens						
Microstructure Modification	2		0.062	0.031	0.756	n.s.
Drill Bits	6		0.25	0.041		
Within Specimens						
Progression of Drilled Holes	2	1	0.136	0.068	2.72	n.s.
Prog. of Drilled Holes x Micro. Modification	4	2	0.088	0.022	0.88	n.s.
Prog. of Drilled Holes x Drill Bits	12	6	0.304	0.025		
Total	26		0.84			

The ANOVA for thrust is presented in Table 14. Only the main effect for progression of drilling reached significance at conventional levels ($p < 0.01$). Neither the main effect for microstructural modification, nor the interaction of progression of drilling with microstructural modification was significant.

It was necessary to determine which of the levels of progression of drilling were significantly different from which others. Orthogonal polynomials were constructed (trend analysis) to test whether there might have been any significant trend in the relationship between progression of drilling and thrust. Results of this analysis indicated that the relationship between progression of drilling and thrust was strongly linear ($p < 0.005$), but there was no indication from these data that this relationship was anything other than linear (see Figure 30). That is, the test of the quadratic component was non-significant.

Table 14. Two-way Factorial Analysis of Variance for Thrust

Source	*Usual Df*	*Conservative Df*	**Sum of Squares**	**Mean Squeare**	*F*	**P**
Among Specimens						
Microstructure Modification	2		0.015	0.0075	0.68	n.s.
Drill Bits	6		0.066	0.011		
Within Specimens						
Progression of Drilled Holes	2	1	0.039	0.019	15.83	0.01
Prog. of Drilled Holes x Micro. Modification	4	2	0.013	0.003	2.5	n.s.
Prog. of Drilled Holes x Drill Bits	12	6	0.015	0.0012		
Total	26		0.148			

The sum of squares stemming from the Cth contrast is defined as:

$$SSC_c = \frac{n\left(\sum_{j=1}^{q} C_{cj}\, \overline{Y}_{.j}\right)^2}{\sum_{j=1}^{q} C^2_{cj}}$$

Therefore, the sum of squares for the linear component is:

$$SSC_{lin} = \frac{9((-1)(.397)+(0)(0.426)+(1)(0.487))^2}{(-1)^2+(1)^2} = 0.03726$$

$$F = \frac{0.03726/1}{0.0012} = 30.375$$

Consulting standard tables of the F statistic for 1 and 12 degrees of freedom (i.e.,

usual degrees of freedom) at $\alpha=0.005$, a critical value of 11.75 was found. Then,

consulting these same F tables for 1 and 6 degrees of freedom (i.e., conservative degrees

of freedom) at α=0.005, a critical value of 18.63 was found. Clearly, the linear trend

component was highly significant. It is very evident that thrust increases linearly in

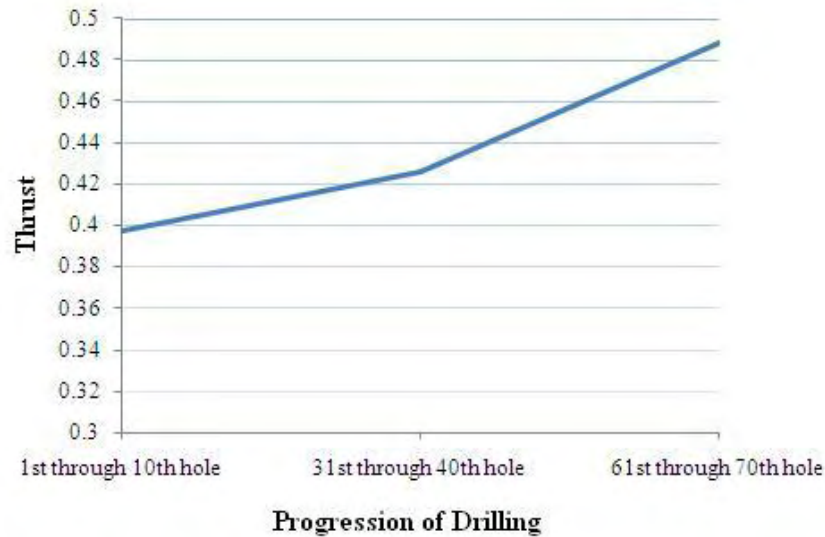response to corresponding increases in the progression of drilling.

Figure 30. Linear Relationship Between Thrust and Progression of Drilling.

For the quadratic component;

$$SSC_{quad} = \frac{9((1)(.397) + (-2)(0.426) + (1)(0.487))^2}{(1)^2 + (-2)^2 + (1)^2} = 0.001536$$

$$F = \frac{0.001536/1}{0.0012} = 1.28$$

Consulting standard tables of the F statistic for 1 and 12 degrees of freedom (i.e.,

usual degrees of freedom) at α=0.05, a critical value of 4.74 was found. Then, consulting

same F tables for 1 and 6 degrees of freedom (i.e., conservative degrees of freedom) at

α=0.05, a critical value of 5.98 was found. Clearly, the quadratic trend component was

not significant when tested against either the usual or the conservative degrees of

freedom; therefore the relationship between thrust and number of drilled holes can only

be shown to be linear.

V. DISCUSSION

The analysis of number of holes drilled in each condition revealed a significant difference ($p<0.05$) between the three microstructural modifications but in the opposite direction from that which was expected. The Sr. modified plus heat treatment condition, instead of allowing the highest number of drilled holes, surprisingly, resulted in the fewest number of drilled holes. The as-cast condition also acted contrary to expectations, allowing the highest number of drilled holes among all conditions. These results were borne out by independent orthogonal contrasts. The number of holes obtained in the as-cast condition was significantly higher than the number obtained in either of the modified conditions ($p<0.05$), but the number of holes achieved in the two modified conditions was statistically indistinguishable. A careful inspection of the cutting tool during drilling proved very helpful in explaining these unexpected results.

A smearing effect, or built-up-edge (BUE), was observed where the aluminum welded itself to the cutting tool as the number of holes increased. This adhesion phenomenon evolved during drilling and seemed to be of a different nature at each stage. At the start of drilling (i.e., when a new drill was used), an aluminum layer did not tend to stick on the drill flutes nor on the point of the tool. However, after a certain number of holes was drilled, an aluminum deposit started adhering to the point of the tool and gradually, this adhesion extended into the flute area where a strong aluminum layer was formed.

Despite the fact that all drill bits experienced the same aluminum adhesion effect, not all of them reacted in the same way to this phenomenon. For example, the bits used to drill into the as-cast condition developed BUE at an earlier point in the progression of drilling than the bits used for the other two conditions. This BUE effect was evident on both the point and the flutes of the tool. However, even when the bits experienced extremely high BUE, a significantly higher number of holes were drilled in the as-cast condition than in the other two conditions prior to tool failure. In the as-cast condition drilling ceased when the tool fractured, an indication that the cutting edge had grown dull. This dulling of the tool led in turn to excessive stress at the cutting edge. By contrast, failure of the bits used to drill the Sr. modified plus heat treatment condition did not result from fracture but from a drilling stoppage. Thus, even though BUE was evident on the point of the tool, this phenomenon was not as acute in the Sr. modified plus heat treatment condition as it had been on the flutes of the tool in the as-cast condition. Instead, in the Sr. modified plus heat treatment condition, the drill failed due to a stoppage of drilling before such a severity of aluminum adhesion became evident, and before the tool fractured.

Of great theoretical importance is the question of why different microstructural conditions led to a different type of tool failure. The explanation for this phenomenon was attributed to the considerable difference in hardness observed between the aluminum plates of the as-cast condition and those of the Sr. modified plus heat treatment condition, and how this difference in hardness interacted with BUE on the point and flutes of the tools. While the as-cast condition had an average Brinell hardness of 45, the plates that were heat treated yielded an average hardness of 82 Brinell. Consequently, the reduced

hardness of the A356 plates from the as-cast condition yielded the highest number of holes, despite the fact that the point and flutes of the drill were covered by aluminum. This means that even though the point of the tool (which cuts and removes material) had high BUE, the drill bit was still able to cut into the aluminum plate just by the pressure exerted by the milling machine. Not surprisingly, tool failure in this condition was driven by the final dullness of the cutting edge of the drill bits and by a build-up of stress at the cutting edge, which caused the drill bits to freeze (i.e., stop spinning) and fracture at the last hole.

In the Sr. modified plus heat treatment condition, the aluminum adherence (i.e., BUE) on the point of the tool caused a change of geometry of the drill bit, impeding a correct cut of the material and evacuation of the chips through the flutes. This same phenomenon happened in the as-cast condition, but the much harder aluminum matrix of the Sr. modified plus heat treatment condition required more than just the pressure exerted by the milling machine to drill the aluminum plate. It required a clean and efficient tool, which should exhibit a sharp point, and flutes free for chip evacuation. Thus, as soon as BUE impeded these operational conditions, the drill bit stopped drilling (i.e., feed in the Z direction was stopped). Furthermore, an inspection of the point of the tool indicated that it was still sharp beneath the built-up-edge, which indicates that it was the adherence of aluminum on the point of the bit that impeded further drilling into the much harder aluminum plate.

This theoretical, but unverified, interaction between hardness and microstructural modification may account for the curious results obtained. In fact, hardness and BUE acted as uncontrolled extraneous variables, which intervened between the independent

and dependent variable, preventing the precise contribution of the independent variable (i.e., microstructural modification) from being fully appreciated.

Discussion of the Repeated Measures Results

The analysis of torque was non-significant on both independent variables, microstructural modification and progression of drilling, and on the interaction between them. In other words, there was no indication from these data that the modification of the A356 microstructure or that progression of the drilling operation led to any meaningful increment in torque. The different physical mechanisms of tool failure among the three microstructural conditions made it difficult to interpret this non-significant result. It is believed that this result was due to the aforementioned interaction of hardness and BUE with microstructural modification, but because hardness and BUE were not incorporated into the experimental design as explicit independent variables, it was impossible to test for the presence or absence of this presumed interaction. More important, early failure of the bits assigned to the Sr. modified and Sr. modified plus heat treatment condition limited the range of the representative holes compared among the conditions.

The bits assigned to the as-cast condition did not reach a stage of terminal dullness until an average of 153 holes had been drilled. Neither the Sr. modified nor the Sr. modified plus HT conditions attained anything near this number of drilled holes. The bits assigned to the Sr. modified condition stopped drilling effectively at an average of 101 holes, and the bits assigned to the Sr. modified plus HT condition stopped drilling at an average of 63 holes.

The original experimental design stipulated that the as-cast condition should "set" the bench mark for "representative" ranges, because the intent was to compare the peak torque and peak thrust in the two modified conditions to "comparable" holes in the as-cast condition. The thinking being, that if the bits were less dull in the two modified conditions, the forces would be significantly lower at the comparable hole range. However, because neither of the modified conditions yielded anywhere near the number of holes achieved in the as-cast condition, it became impossible to use the as-cast condition as the bench mark for defining representative, or comparable hole ranges. Instead, the representative hole ranges had to be defined according to the highest number of holes obtained in the Sr. modified plus HT condition, which yielded the fewest number of holes of any of the three conditions.

Due to the uncontrolled influence of hardness and BUE (i.e., hardness in the HT condition only, and BUE in all three), it was not possible to deploy the drills assigned to the two modified conditions to their points of "terminal" dullness. Because these bits never reached terminal dullness, the number of drilled holes potential to these conditions could not be observed. Assuming this conclusion to be correct, had it been possible to advance the progression of the drilling operation in the Sr. modified and Sr. modified plus heat treatment conditions to their respective points of terminal dullness, meaningful variations in torque might well have been observed, across the levels of progression of drilling and microstructural modification.

This conjecture can only be characterized as highly speculative, however, since it was not possible to advance the progression of the drilling operation to a point of terminal dullness in either of the modified conditions, and since it was believed that the

hypothesized, but unverifiable, interaction of material hardness and BUE contributed to this outcome.

The analysis of thrust revealed that modification of the microstructure of A356 plates had no influence on the thrust generated in each condition. However, a comparison of peak thrust generated among the levels of progression of drilling namely the average of the first ten holes, the 31th through 40th holes, and the 61st through 70th holes showed a significant increase in thrust as the number of drilled holes increased. Furthermore, this relationship between number of drilled holes and thrust was demonstrated to be strongly linear ($p<0.01$).

At the first ten holes drilled in each condition, low thrust was generated because the point and the flutes of the drill bit were clean and the chips were able to properly evacuate the hole. However, as more holes were drilled, BUE was accumulated on the point of the tool and progressively on the flutes, requiring more thrust to be applied to the drill bit in order to cut into the material. At the last representative holes, the highest thrust was generated because the geometry of the tool completely changed. At this stage, the point of the tool completely lost its capability to cut into the material. This linear relationship between progression of drilling and thrust was apparent across all three microstructural conditions, but it was not possible to establish any difference in thrust among the three microstructural conditions. The absence of a significant main effect for microstructural modification can be explained by, and inferred from a visual inspection of the drill bits. The Sr. modified plus heat treatment condition had a harder structure than the as-cast condition, but the bits used to cut into this heat treated condition developed considerably less BUE on the point of the tool. Consequently, the bits assigned

to the Sr. modified plus heat treatment condition retained their geometry longer, due to reduced BUE, but these bits were required to drill into a much harder material. By contrast, the cutting tools used to cut into the as-cast condition developed much higher BUE at a much earlier stage in the progression of drilling, which completely changed the geometry of the tool inducing a poor cut capability. However, this fact did not impede the drills assigned to this condition from effectively cutting the much softer material.

It was hypothesized that the aluminum plates from the Sr. modified plus heat treatment condition would yield the greatest UTS and elongation values. The data collected agreed with the anticipated enhanced UTS values, but were contrary to the expected elongation levels. The reason for such low levels of elongation can be explained by the shorter aging process (3 hours) to which these plates were subjected. As precipitation (aging) begins to occur, the material begins to harden and the strength increases, while there is a corresponding reduction in ductility. After a sufficiently long period of aging (10-12hrs), the material reaches a peak strength value. This point corresponds to a minimum in elongation. Subsequently, the strength remains fairly constant at the peak value, while elongation increases (26). Therefore, the recovery process that elongation should experience with longer periods of time was not possible in this study. In fact, long periods of aging are not common in the manufacturing industry due to the high costs associated with the process, and a high probably of dimensional change of the heat-treated parts.

The form and structure of the chips collected during the drilling of the three different conditions studied provided evidence of their mechanical properties. While the chips collected from the Sr. modified plus heat treatment condition were of a

discontinuous and segmented structure, due to poor ductility (i.e., low elongation) of the material, the chips from the as-cast condition presented a long, curly and continuous structure. The Sr. modified condition generated the longest and curliest chips, because this condition possessed the greatest ductility (i.e., the highest values of elongation).

VI. CONCLUSIONS

- The analysis of number of holes drilled in each condition revealed a significant difference (p<0.05) between the three microstructural modifications but in the opposite direction from that which was expected.

- The number of holes obtained in the as-cast condition was significantly higher than either of the modified conditions (p<0.05), but the number of holes achieved in the two modified conditions was statistically indistinguishable.

- A considerable difference in hardness was observed between the aluminum plates of the as-cast condition and those of the Sr. modified plus heat treatment condition. While the as-cast condition had an average Brinell hardness of 45, the plates that were heat treated yielded an average hardness of 82 Brinell.

- Consequently, the reduced hardness of the A356 plates from the as-cast condition yielded the highest number of holes, despite the fact that the point and flutes of the drill were covered by aluminum. Not surprisingly, tool failure in this condition (i.e., fracture) was driven by dullness of the cutting edge of the drill bits and by a build-up of stress at the cutting edge.

- By contrast, the hardening effect of thermal modification on the aluminum matrix of the Sr. modified plus heat treatment condition made this condition much less

tolerant of BUE on the point of the cutting tool, causing a stoppage of the drilling operation before excessive tool wear became evident.

- The analysis of torque was ambiguous and equivocal. Neither the main effect for microstructural modification not the main effect for progression of drilling was statistically significant, nor was the interaction of the two. It is difficult to interpret these results in any meaningful way. Certain hypotheses have been offered, for the sake of guiding future research, but these conjectures are speculative at best, and await verification through more refined methods.

- The analysis of thrust revealed a significantly linear relationship ($\alpha=0.01$) between progression of drilling and thrust. As the number of drilled holes increased, thrust increased linearly, regardless of microstructural condition. Visual inspection of the drills assigned to the three microstructural conditions revealed that the underlying physical mechanics of the cutting operation driving this linear increase of thrust was different for each of the three conditions.

- It was hypothesized that the aluminum plates that were heat treated would acquire the greatest UTS value and the greatest elongation. The data collected agreed with the hypothesized higher UTS values, but were contrary to the anticipated increase in elongation. The reason for such low levels of elongation can be explained by the shorter aging process (3 hours) to which these plates were subjected at which these plates were subjected.

- The chips collected from the Sr. modified plus heat treatment condition were of a discontinuous and segmented structure, due to a poor ductility and low elongation

of the material, the chips from the as-cast condition presented a long, curly and continuous structure. The Sr. modified condition generated the longest and curliest chips, because it possessed the greatest ductility and had the highest levels of elongation.

VII. RECOMMENDATIONS

Regarding recommendations for further studies, cutting fluid should be used during drilling to avoid BUE formation on the drill bits. It is believed that BUE was one of two variables that may have prevented the detection of an effect for microstructural modification on tool life by changing the geometry of the point of the tool and preventing a correct chip evacuation through the flutes of the tool. The second uncontrolled variable that may have prevented the detection of an effect for microstructural modification was the increase in hardness acquired by the heat treated plates, which in combination with BUE limited the number of holes achieved in the Sr. modified and the Sr. modified plus heat treatment conditions.

It is also recommended that a future study incorporate heat treatment into the experimental design as an explicit independent variable. Had heat treatment been fully crossed with microstructural modification in the current study it would have been possible to test for the hypothesized interaction of hardness with microstructure. Because it was not possible to test for this interaction in the current study, this hypothesis remains unsubstantiated, and awaits further investigation.

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