A380 ALUMINUM HOT CHAMBER DIE CASTING

by

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To those above and those still here that have given so much for me, all I can say is this.

Thank you.

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SYMBOLS

in	Inch
kN	Kilo newton
ksi	Kilo pounds per square inch
min	Minute
mm	Millimeter
psi	Pounds per square inch
s	Second
W	Watt

LIST OF ABBREVIATIONS

HCDC	Hot Chamber Die Cast
HPDC	High Pressure Die Cast
HPU	Hydraulic Power Unit
CCDC	Cold Chamber Die Cast

GLOSSARY

A380	Aluminum alloy A380
Shot	The colloquial term for a die casting cycle.

ABSTRACT

A hot chamber die casting machine designed for zinc was donated to Purdue University. This machine was slated for retrofit of components necessary for aluminum hot chamber die casting. Existing components designed for zinc, mainly H-13 and cast iron, do not have the necessary service life to economically produce castings due to chemical attack on machine components from molten aluminum. Multiple systems were redesigned, including the pot, plunger, gooseneck, furnace, and cooling lines. All components were upgraded to allow for the higher service temperatures needed for molten aluminum, along with a niobium gooseneck and anviloy nozzle to resist chemical attack of injection components. Once design and retrofitting were complete aluminum alloy A380 was used in conjunction with a niobium gooseneck design to create tensile bars. These tensile bars were subsequently tested and mechanical properties evaluated.

CHAPTER 1 - INTRODUCTION

1.1 Research Questions

Can an AVNET H-35E hot chamber die casting machine designed for lower temperature metals such as lead and zinc be retrofitted to create aluminum tensile samples? What is the service life a niobium gooseneck proposed to be used in the AVNET H-35E when using A380 alloy? What are the mechanical properties of A380 alloy tensile samples created using the niobium gooseneck while employing the hot chamber die casting process with the AVNET H-35E?

1.2 Problem Statement

Existing die cast processes suitable for aluminum alloys introduce defects into castings due to inherent issues specific to the process. These processes produced defects such as gas entrapment, cold flakes, and oxide inclusion. When these defects occurred significant losses in mechanical properties were seen in the castings. These losses resulted in the rejection of the part. More importantly, these defects precluded the use of these alloys in critical structural components without highly optimized and specific solutions. It had been theorized that a hot chamber process would produce better part quality with significantly reduced defects but currently used technology does not allow for the economical use of hot chamber with aluminum alloys due to the caustic environment of the molten aluminum.

1.3 Scope of Work

The scope of this project was to develop, design, and retrofit components of the AVNET H-35E hot chamber die cast machine to allow for testing of a niobium gooseneck with A380 alloy. This required the refit and rebuild of multiple machine systems, including injection, melting, and cooling. Once these systems were modified to facilitate the use of A380 with the niobium gooseneck tensile samples were created. The gooseneck was operated until failure of the injection system to determine longevity. Of the A380 tensile samples created, all were tested to failure using a tensile tester to obtain the sample's mechanical properties. These properties were then compared to cold chamber and other hot chamber as cast properties and evaluated. After testing was completed additional next steps were identified to refine and improve upon the redesigned hot chamber process.

1.4 Project Significance

Current cold chamber die casting processes carry a number of disadvantages, many of which are remedied in the hot chamber process. These problems caused an increase in machine tool wear that results in high process expenses along with an increase in the number of defects in castings compared to those obtained from the hot chamber process. Molten aluminum was corrosive to many materials at the elevated temperatures required for die casting. Whether the system be cold chamber or hot chamber, both systems were subjected to the effects of molten aluminum on their steel components. "In particular, casting metals with a high melting point and high affinity to iron are not appropriate materials. As a matter of fact, aluminium alloys have seldom been used in hot chamber die casting processes due to their high melting points and strong erosion occurring between the aluminium and iron injection systems" (Okayasu, et al., 2009 p.375). **"**However, the hot chamber die casting process is not used for making aluminum die castings because gooseneck is usually made of a ferrous alloy which is prone to chemical attack by molten aluminum" (Han, et al., 2020 p.2). The niobium gooseneck proposed, if effective, would radically change the effectiveness of hot chamber machines with regards to aluminum. With current goosenecks made of H-13 steel these goosenecks failed rapidly due to immersion in molten aluminum. Niobium was thought to be superior due to its extremely limited reactivity when immersed in aluminum. With the knowledge of hot chamber benefits for lower temperature metals, such as zinc, if such benefits could be applied to aluminum castings significant economic savings could occur. Significant improvements in casting integrity and associated mechanical properties are seen when the hot chamber process was used compared to mechanical properties of cold chamber castings.

1.5 Process Overview

The die casting process can be broken down into six major component processes. Die lube is applied to cool the die halves to operational temperatures, ensure the surfaces are coated to reduce soldering, and to facilitate easier part removal. Once completed, the dies are closed through the use of a hydraulic clamping unit. Molten metal is then injected into the die until filled. The die and molten metal are then cooled, continuing until the molten metal has solidified sufficiently to be removed. The die is then opened by the clamping unit and the die halves separated. Parts are then pushed through the use of ejector pins and either removed by hand, robot, or gravity. As cast parts will retain a gating and riser system necessary for metal injection and part integrity, as well as flashing along the die parting line. These items must be removed from the casting through a variety of methods, such as machining or hydraulic trimming. Once completed the finished casting is transported for inspection and post processing.

1.5.1 Die Lube Application

Die lube application is seen as critical to both machine longevity and cast part surface finish. At the beginning of each casting cycle, die lube is applied to coat die surfaces exposed to molten metal. The lube was designed to reduce soldering of metals onto the die surfaces and to also facilitate part removal. The lube was typically applied in a mix ratio with water, the ratio dependent upon the type of lube being used. The mix was then applied until the die was cool enough for the lubricant to adhere to the die. The extended spraying time is due to the Leidenfrost effect creating a steam barrier between the lubricant and die surface as water flash boils into steam. The barrier prevented lubricant from directly contacting the die surface. Once thoroughly cooled to the point that sufficient die lube adhered to the surface of the die, lubricant application was stopped. Residual liquid was allowed to evaporate, upon which the clamping cycle was commenced.

1.5.2 Clamping

After die lube application, the casting die must be closed. One half of the die is fixed to the molten metal injection system while the other half is mobile. The mobile die, or movable die, is moved along tie bars to facilitate alignment and provide the mechanical strength necessary to resist deflection during the clamping process. The movable die is actuated, typically through hydraulics, and pressed against the fixed die. Sufficient force must be applied throughout the injection process to ensure the force of injection does result in the forced opening of the die halves. The force is referred to as tonnage.

1.5.3 Molten Metal Injection

Once the die halves have been closed the mold is ready to be filled. Hot chamber and cold chamber die casting machines have fundamentally different injection processes. Hot chamber uses an gooseneck immersed in the molten metal while cold chamber machines use a shot sleeve that molten metal is ladled into. Both machines use a plunger, typically hydraulicly actuated, to push metal through the injection system and into the mold. Metal is typically injected at a rapid rate to ensure that metal does not solidify before completely filling the casting. This is especially critical in cold chamber die casting, which will be explained in later chapters. Molten metal will shrink as cooled and allowed to solidify. The injection pressure is held until solidification is completed to reduce defecting due to shrinkage as the metal solidifies.

1.5.4 Die and Part Cooling

After molten metal is removed from the holding furnace it began to lose energy and solidify. The energy loss was notably seen in the cooler die halves that experienced a large temperature gradient when filled with molten metal. These die halves fundamentally exist as large heat exchangers. The halves are fitted with independent cooling lines, lines which water or other liquid mediums such as oil were pumped through to facilitate heat removal. The purpose of these lines was to increase cooling rates from the natural unassisted equilibrium cooling rate of the metal as the dies could not be opened until the metal is solidified. This accelerated cooling rate was a major advantage of the die casting process.

1.5.5 Part Removal

After solidification parts are removed. The moveable die half will open and expose the casting. This casting will then be separated from the moveable die half by ejector pins that push out from the moveable die half. Castings are then removed by hand, robot, or gravity depending on multiple factors such as die design, casting weight, geometry, and automation.

1.5.6 Gating and Flashing Removal

All die cast parts require a gating and runner system to facilitate injection into the cavity of the desired part within the die. The gating system must be removed before detailed inspection and post process machining can begin. Gating, runners, and flashing can be removed be either manual methods or automated methods. Methods such as cutting by manual bandsaw or hydraulic trimming have been effective solutions. As the industry continues to advance and automate many removal and trimming operations have been moved to robots with electric or hydraulic shears.

1.6 Advantages of Die Casting

High pressure die casting (HPDC) machines generate much higher levels of productivity when compared to other casting processes such as gravity casting. "Casting cycle times can range from 10 s for a small machine to up to 2 min for a large machine." (McInerney II, 2008, p. 724) Highly complex part geometry can be cast, including geometry with thin wall thicknesses unsuitable for other types of casting. This was due to the high injection pressures that force the molten metal into the mold. The ability to cast with thinner wall thicknesses allows for material reduction, lowering overall casting weight and material costs. Because of the ability to use complex levels of geometry, cores, pins, and slides in the casting die, more complex parts can be produced. This allows for a reduced number of components in the assembled part (Butler, 2008, p.716).

1.7 Disadvantages of Die Casting

HPDC processes, like other processes, experience a number of downsides associated with the process of creating the castings. "The high tooling costs of high-pressure die casting make short production runs generally uneconomical." (Butler, 2008, p. 717). The costs of these tooling items associated with the HPDC process limit entry to the market with this process. Associatively, high tooling costs, especially in the die, will limit potentially limit iterative changes to geometry as a cost-benefit analysis must be done given the extensive price of die casting dies. Die casting itself is limited to a select group of metals, particularly non-ferrous. Ferrous alloys are generally seen as uncastable due to the interactions with components of the die cast machine. Die casting machines themselves are highly complex electro-mechanical systems. These systems are generally more expensive than other casting processes for both capital equipment purchases, and the associated maintenance. This can be directly tied to the higher levels of complexity in the process, along with the higher stresses and associated machine wear due to higher casting pressures.

1.8 Assumptions

- Alloys cast were of the nominal A380 composition as listed in ASTM B85.
- Alloy composition did not deviate from nominal during melting and casting.
- All thermocouples were operating within tolerance.
- All machine controls, such as timers, displayed accurate values.
- MTS tensile tester load cell, crosshead, and extensometer were operating within tolerance.

1.9 Limitations

- Limited documentation was available for the AVNET die cast machine.
- Spectrometry service was not available during the project.
- Many components, such as heaters and burners, were hard to source for the AVNET machine due to the increased temperature requirement and small machine size.
- Only A380 alloy was available for use, instead of the 380 alloy for hot chamber specified in ASTM B85.

1.10 Delimitations

- Cast part microstructure was not analyzed.
- Only A380 alloy was used.
- Part metallurgy was not analyzed.
- Die geometry was not changed from the initial geometry designed for zinc.

1.11 Summary

The project raised multiple research questions to identify if an existing hot chamber die cast machine at Purdue University could be retrofitted with new alternative gooseneck materials, such as niobium, to create A380 tensile samples. High pressure die casting processes elements, along with associated advantages and disadvantages inherent in the manufacturing process were identified. Project assumptions, limitations, and delimitations were addressed. Further review into diecasting processes and necessary technologies were reviewed in the next section, the review of the literature.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Cold Chamber Die Casting Process and Components

“The cold chamber high-pressure die casting machine performs several functions during the die casting process and is essentially two machines that work together. The two machines are called the clamp end and the shot end.” (McInerney II, 2008, p.724) Cold chamber die casting refers to the process in which molten metal is poured into a shot sleeve through the use of a ladle. This metal is then pushed through the sleeve at high speed and into the die through the use of a plunger. For the case of aluminum, shot sleeve temperatures are held below the solidus point of the metal to increase component life of the plunger and sleeve. Due to these lower temperatures the casting process must be completed quickly to ensure metal remains molten and retains its fluidity to completely fill the mold. The die halves to be filled are clamped and held closed through the use of hydraulics. Once the metal has been injected into the die, it begins to cool. This is accelerated through the use of cooling lines throughout the die. These lines are generally filled with water, but oil is prevalent in some applications. After the metal has solidified inside the die halves the hydraulic system will activate and pull the die halves apart. Ejector pins inside the mold then push and free the casting from the die. Castings can be removed by hand, robot, or pushed out completely and into a parts chute. Die lube is then applied to both cool the die and treat the surface. Once completed the die closes and the process repeats. Figure 2.1 shows a diagram of the major components outlined below.

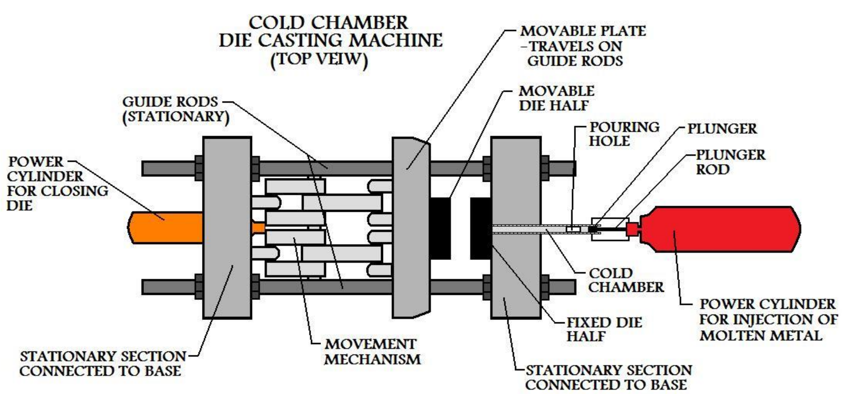

Figure 2.1 Cold chamber die cast machine schematic (The Library of Manufacturing, n.d.)

2.1.1 Shot End

The shot end of the machine contains the cold chamber die casting machine contains the shot cylinder, known as a shot sleeve. Metal is poured into this sleeve from a furnace outside of the machine by way of a ladle. The ladled material is then pushed through the shot sleeve by way of a ram, or more commonly known as a plunger. The plunger moves through the shot cylinder taking care to limit disturbances to the liquid metal while injecting it into the die at high pressures and speed.

2.1.1.1 Ladle

The casting process between hot chamber and cold chamber is differentiated by the metal injection process. In a cold chamber machine metal is ladled into a shot sleeve to later be injected into the die cavity to create the casting as seen in Figure 2.2.

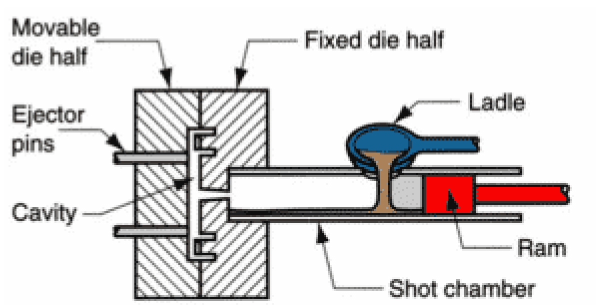

Figure 2.2 Cold chamber die casting ladle operation example (*Hot Chamber vs. Cold Chamber Die Casting*, 2021)

The ladle is designed to transport molten metal from a holding furnace separate from the die cast machine and fill the shot sleeve with the necessary amount of metal to complete the casting. The vast majority of ladles are made of ceramics due to both the ceramic materials thermally insulating properties and resistance to thermal shock. Ladle materials must retain low thermal conductivity to minimize overall temperature loss in transition from the furnace to pouring into the shot sleeve. Excessive thermal losses could lead to increased defecting or premature solidification in the injection system.

2.1.1.2 Shot Sleeve

After the ladle has transported molten metal from the furnace it is poured into a shot sleeve, also referred to as shot chamber or cold chamber. This sleeve contains the injection plunger while also mating to the fixed die half as previously seen in Figure 2.2. The sleeve does not remain immersed in metal, it only contains enough for a single casting. This distinction is why the process is referenced as cold chamber, compared to a hot chamber that immerses the injection system in molten metal. In essence the shot sleeve is a temporary holding container for a single casting's worth of aluminum, holding molten material until the plunger injects the molten metal into the die.

2.1.1.3 Plunger

As seen previously in Figure 2.2 the plunger, also known as a ram, rests inside the shot sleeve. The purpose of this ram is to push molten metal poured into the shot sleeve at high speed and pressure to ultimately fill the die cavity. Sealing between the ram and shot sleeve is accomplished by a series of expanding steel rings. This plunger moves through at multiple speeds in an attempt to limit defects associated with the use of a shot sleeve in the injection process.

2.1.1.3.1 Cold Chamber Plunger Kinematics

Cold chamber die casting machines employ a highly complex series of carefully timed movements of the plunger to minimize castings defects inherent to the cold chamber process. For cold chamber die casting, "The main disadvantage of this process are gas entrapment and oxide formation due to the highly turbulent flow of metal in the chamber and die cavity." (Fiorese & Bonollo, p.3731). Modern cold chamber machines are equipped with highly accurate proportional hydraulic servo valves to obtain the ability to minutely adjust ram speeds and pressures. These adjustments are made to limit wave formation in the metal to be cast. Wave formation made in the metal to be cast leads to gas and air entrapment which is directly linked to porosity in cast parts. The overall injection process of the plunger can be broken down into three major sections. The first section is the filling of the shot sleeve and subsequent movement of the plunger. The plunger will move forward in the sleeve, usually at lower speeds, until it passes the cutout in the shot sleeve through which molten metal was ladled. After this passage, the shot sleeve rapidly accelerates and builds pressure to fill the die cavity while attempting to minimize waves in the shot sleeve. Once the die is filled, the third stage begins. The plunger maintains pressure within the shot sleeve and die in an effort to continue to feed the die. As molten metal solidifies in the die, pressure must be maintained to encourage the flow of metal into the die as solidified sections begin to shrink. Failure to do so results in shrinkage porosity. When completed the plunger will retract and the casting cycle is repeated.

2.1.2 Clamp End

The clamping end of a cold chamber die cast machine consists of two major areas. The clamping unit which contains the support platens, mechanical members to accommodate high pressure clamping, and the clamping power source, normally a hydraulic cylinder as seen in Figure 2.3. The clamp end also contains the die halves, in which molten metal is injected to form castings of required geometry.

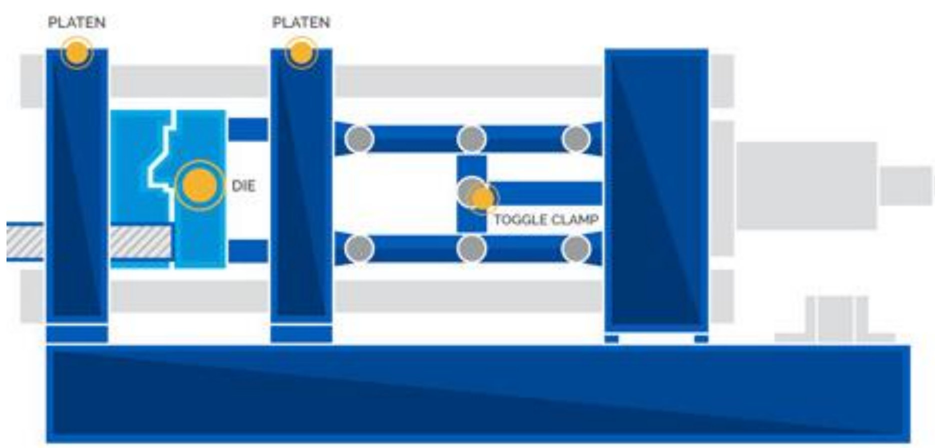

Figure 2.3 Cold chamber plunger with die and clamping unit (*Operating sequence of the cold chamber die casting process.*, 2021)

<u>2.1.2.1 Clamping Unit</u>

The clamping unit on a cold chamber die cast machine consists of a series of platens, tie bars, and mechanical linkages to exert force upon the die halves. One platen is fixed, upon which the non-movable side of the die along with the shot sleeve are attached. A series of tie bars attach through both the fixed and mobile platens, culminating in a load bearing plate upon which the clamping cylinder mounts. The cylinder, usually hydraulicly powered, drives the mobile platen and applies the force necessary to keep the die closed during casting operations.

2.1.2.2 Die

The dies used in cold chamber die casting are typically made of a high carbon steel that is suited for large amounts of thermal shock while pairing with a high toughness and hardness. Because of the large capital investment die life is a critical area upon which design considerations must be made. The die itself is a multi-part mold, at its most simplistic, consisting of two halves with either a vertical or horizontal parting line. These dies are machined to create a negative cavity that mimics the desired as cast part geometry of finished parts. Since the fundamental function of a die cast machine is to take molten metal and solidify it into a finished casting of the required geometry the die serves as the solidification area. To allow for rapid use of the machine which is a key advantage of this process dies must be cooled. Typically cooling lines are machined throughout the die over key areas behind the part geometry. The die itself is typically cooled with water or oil. For the fundamental view of the casting process, the die is a large heat exchanger.

2.1.3 Cast Metals Used

Cold chamber die casting metals tend to be of a higher melting temperature. A cold chamber unit not storing metal continuously inside its shot cylinder component, damage from higher temperature metals, such as aluminum or magnesium, is minimized. This type of injection system allows for higher temperature metals, such as aluminum, to be cast economically and quickly.

2.2 Hot Chamber Die Casting Process and Components

Unlike the cold chamber process hot chamber machines do not require metal to be poured into a shot sleeve for every casting. Instead hot chamber machines have a gooseneck that is immersed in a holding pot filled with molten metal. The molten metal gravity fills the gooseneck through fill holes below the surface of the melt. Molten metal is then pushed through the gooseneck by way of a plunger. The molten metal is then pushed through a nozzle attached to the gooseneck that maintains a slight positive angle to eliminate drips due to gravity. The outlet of the nozzle is attached to the inlet sprue bushing of the die and metal pushed through and into the die. Metal is then allowed to solidify inside the die, accelerated through the use of cooling lines throughout the die. The die halves are opened, and parts removed much in the same way as cold chamber die casting. Figure 2.4 shows a machine diagram highlighting the major components talked about later in this section.

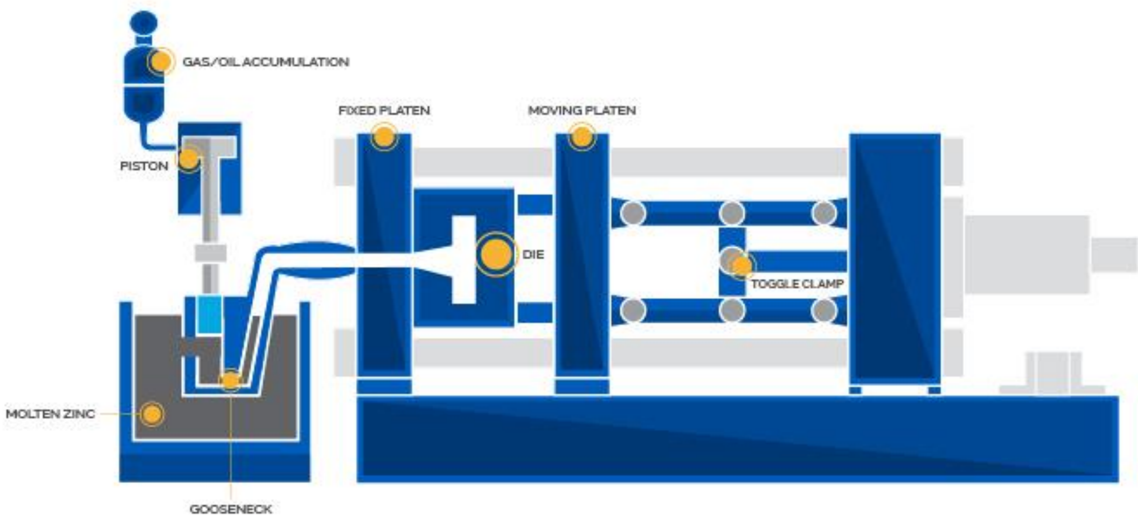

Figure 2.4 Component view of major hot chamber systems (*Hot Chamber Die Casting*, 2021)

2.2.1 Holding Pot

The holding pot, as seen in Figure 2.5, contains the molten metal.

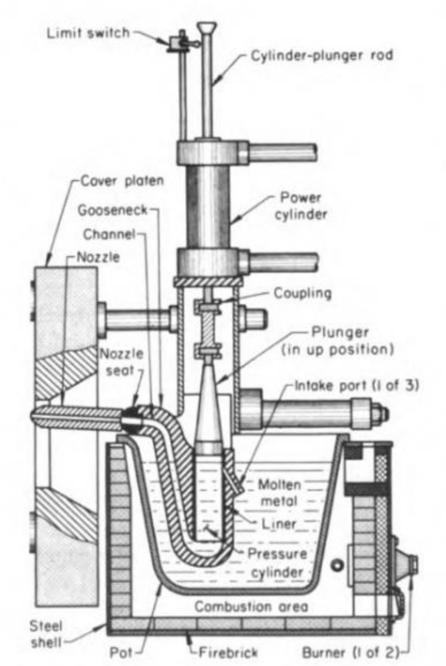

Figure 2.5 Hot chamber holding furnace with gooseneck and plunger (Davis, 1995, p.251)

The system can be designed to either hold molten metal or directly melt the molten metal without the use of a secondary furnace. One such advantage would be that the pot could be covered with a shielding gas, reducing oxidation of the molten metal. The holding pots are typically coated to reduce molten metal adhesion to the surface.

2.2.2 Gooseneck

The gooseneck is a u-shaped component of the injection system that is constantly immersed in molten metal during casting operations. This metal is injected into the part by way of a plunger, which is inserted in the gooseneck. Since the gooseneck is immersed in the molten metal bath, the injection system is considered hot as they should maintain the same temperature.

2.2.3 Plunger

For hot chamber die cast machines, the metal is forced through the gooseneck and into the die cavity by way of a plunger. The plunger fits inside the gooseneck as previously seen in Figure 2.5. Sealing between the gooseneck and plunger is achieved by expanding sealing rings fitted into grooves on the plunger. "These machine components are normally made from tool steel or stainless steel" (Goodwin, p. 719). The plunger is actuated by a hydraulic shot cylinder powered by a hydraulic power unit.

2.2.4 Nozzle

The hot chamber nozzle is situated between the gooseneck and sprue bushing on the fixed half of the die as seen previously in Figure 2.5. The nozzle is fixed with a half-spherical end which matches a similar radius on the die bushing.

2.2.5 Die

The die contains the part geometry, cooling lines, and ejector pins necessary for molten metal to be injected into the part and subsequently solidified castings ejected. Typically made out of H-13 steel or other high carbon tool steels due to resistance to thermal shock and high wear resistance.

2.2.6 Cast Metals Used

Typical hot chamber machines are forced to use lower temperature metals such as zinc, lead, and tin to ensure longevity of their injection components. (Butler, 2008, p. 715). Metals with higher temperatures, such as aluminum, tend to rapidly degrade the injection components continuously immersed in the molten metal. With these material's tendency to diffuse iron out of their steel components continuous high temperature immersion directly leads to higher maintenance costs and subsequent downtime, completely negating the advantages seen in the hot chamber process.

2.3 Cold Chamber Die Casting Defects

The cold chamber process's method of metal injection leads to several inherent defects such as cold flakes, oxidation, and porosity. These defects cause discrepancies in the microstructure of the cast parts, and in some cases voids in the metal. These defects and the resulting decrease in mechanical strength lead to limitations for use and part geometry.

2.3.1 Cold flakes

Cold flakes are inherent to the cold chamber die casting process due to the use of the shot sleeve. The shot sleeve operates at a temperature much lower than the molten metal being poured into it, leading to a thin solidification layer on the shot sleeve. “The initially solidified layer of melt is broken into small parts, and these parts distribute in the molten metal to remain as cold flakes” (Ahamed & Kato, 2008, p. 1622) With the addition of these cold flakes mechanical properties are directly affected. The cold fakes prevent growth of dendrites in some areas, resulting in relative weakening in that area of the microstructure. The randomness of these defects leads cold chamber castings to not be suitable for high strength structural castings.

2.3.2 Oxidation

Like cold flakes, oxidation related defects are again directly related to both the injection process, and the fact that metal must be ladled from another furnace into the shot sleeve. To begin, metal must be introduced to the shot sleeve by way of a ladle. The ladle must be dipped into the molten metal bath, cutting through the oxide layer on the top of the metal in contact with the atmosphere. Oxidation can also be introduced to the cast parts by way of the injection ram speed. Excessive wave motion during injection by way of creating turbulent flow can lead to excessive oxide creation during the injection process. Both of these defect modes lead to discrepancies of the microstructure and subsequent dendrite growth resulting in lower mechanical strength.

2.3.3 Porosity

Porosity can be introduced to cast parts through multiple avenues in the cold chamber process. One of the first is insufficient injection pressure during solidification of the casting. Pressure during solidification is increased in an attempt to continue to feed the casting metal as it begins to solidify. A lack of pressure leads to tearing and void creation as the metal solidifies and shrinks. Porosity can also be obtained from gas entrapment during the shot process. If a turbulent wave motion is made in the injection cylinder there is a higher likelihood of entrained gasses making it into the casting cavities. These gasses displace molten metal, leading to voids and drastically reduced strength.

2.4 Die Soldering

Die soldering is a critical lifecycle issue for many machine components. Generally an issue with higher temperature metals such as aluminum, these metals when at elevated temperatures prove damaging to the critical machine surfaces in both the injection systems and the dies. Soldering can be reduced to a degree by employing coatings and lubricants to surfaces to provide physical barriers between steel machine components and high temperature alloys to be cast. Die soldering must be minimized for cost effective production runs of cast parts.

2.5 Ceramics used in hot chamber goosenecks

Okayasu et. al performed multiple experiments using ceramics as alternative gooseneck materials in the die casting process. The first iteration resulted in failure after only 30 shots due to an alignment issue between the injection plunger and the gooseneck. Such alignment issue lead to galling and premature wear of the components, eventually leading to a cracking of the gooseneck. Later attempts to redesign the injection plunger to allow for more degrees of freedom to perform self alignment proved to be successful. Other ceramic gooseneck designs created thousands of parts before failure. It is important to note that Okayasu et. al performed their experiments and produced valid tensile testing results of the subsequent castings. Hot chamber units produced approximately 337MPa of ultimate tensile strength compared to 287MPa for cold chamber units. Yield strength saw a muted, but still significant increase with 220 MPa for hot chamber, and 210MPa for cold chamber.

2.6 Niobium mechanical properties

ASTM B393 defines the standard specifications for niobium and niobium alloys. It specifically applies to strips, sheets, and plates. Looking specifically at 99% niobium, 1% zirconium commercial grade alloys are considered type 4. For the annealed condition, the alloy must meet a minimum ultimate tensile strength of 28,000 psi, a yield strength (.2% offset) of 18,000 psi, and an elongation of 20%. (ASTM International, *B393,* 2018)

2.7 Niobium Oxidation

Pure niobium particularly susceptible to oxidation at temperatures above 500°C. Significant weight loss of niobium and subsequent niobium oxide creation was noted by Arbusov and Chuprina. The experiments were conducted with niobium exposed to atmosphere, as will be done in this project. It is important to note oxidation increases somewhat linearly based upon temperature and time.

2.8 A380 Mechanical Properties

ASTM B85 is the standard specifications for aluminum alloy die castings, created by the American Society for Testing and Materials. Table 2.1 details the chemical composition requirements of A380.

Table 2.1 Chemical Requirements of A380 (ASTM International, *B85*, 2018, p. 2)

Desig.	Si	Fe	Cu	Mn	Mg	Ni	Zn	Sn	Al
A380	7.5-9.5	1.3	3.0-4.0	0.5	0.1	0.5	3.0	0.15	Bal

2.9 HCDC Casting Simulations

Previous project work was done by Isenberg using this machine. One of the major areas was simulation work detailing shot parameters for A380 alloy used in the hot chamber process. Given that all of the shot components in hot chamber system are preheated and at equilibrium, shot temperatures were simulated at 620°C. Shot speed was simulated at 0.127m/s. (Isenberg, 2018, p80.) These simulations showed high levels of air entrapment in the finished castings.

CHAPTER 3 – RESEARCH METHODOLOGY

3.1 Avnet Die Cast Components

The existing AVNET H-35E was inoperable upon donation to Purdue University. Previous project work was done to repair critical machine components and return it to operable status for use with zinc alloys. This machine was reconfigured and redesigned to accommodate new components in the pursuit of casting aluminum alloys, specifically A380. Virtually every machine system encountered a need for redesigned and replaced components to support the new operating temperatures required with A380.

3.1.1 Hydraulic System

The AVNET H-35E was configured with a hydraulic power unit and associated control console to control die position, clamping, and injection as seen in Figure 3.1.

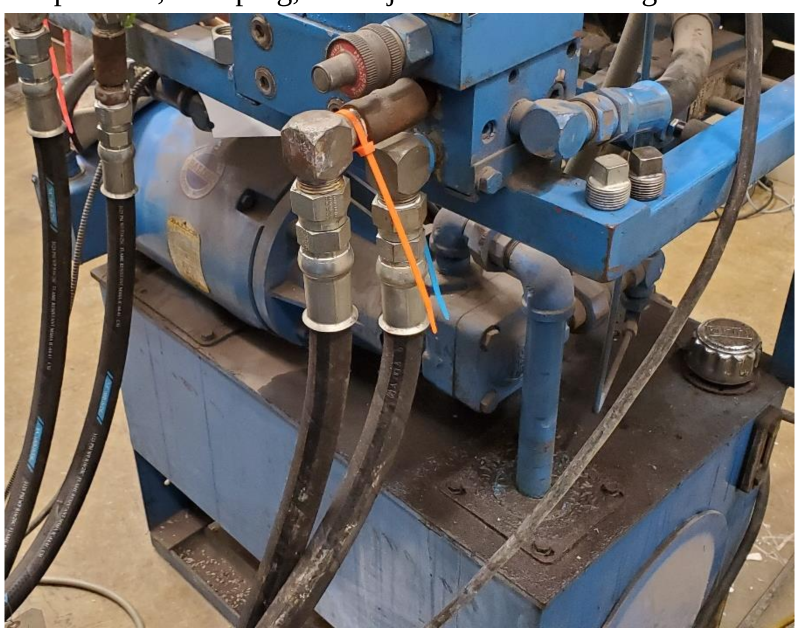

Figure 3.1 AVNET H-35E Hydraulic power unit

The HPU was configured with a 25 gallon reservoir and filled with fire resistant hydraulic fluid. Primary voltage was rated at 480 volts, with a total amperage of 30 amps. The motor was rated at 10 horse power and fitted with a pump rated for 10.8 gpm at 1200 psi. In addition to the primary hydraulic circuit an accumulator was installed for surge pressure. The accumulator was rated for 2000 psi, with a 0.5 gallon capacity. Die and plunger speeds were regulated through the use of needle type flow controls.

3.1.2 Heating system

The AVNET H-35E's existing heating system was designed for lead and zinc alloys in the 390 degrees Celsius range, it was expected that significant rework of both the main furnace burner for the holding pot and the nozzle heaters would require extensive upgrades. Due to the smaller scale of the machine, along with the higher temperature requirements for aluminum typical components for this size of hot chamber machine are not suitable. Multiple areas of work were identified, including the main furnace burner and nozzle heaters.

3.1.2.1 Furnace burner

The existing burner on the AVNET H-35E was an open flame burner, using natural gas and compressed air. Natural gas service was 2 psi nominal, 1.8 psi at the machine given pipe losses. The machine was equipped with two gas regulators, both of which were set to 2.0 psi. The original natural gas burner was rated for 130,000 BTU. It was theorized given the additional heat loading that a burner in the 225,000-250,000 BTU range will be needed to account for the higher melting temperature of A380.

3.1.2.2 Nozzle heaters

The existing nozzle heater consisted of a natural gas and compressed air open flame torch. The torch was positioned behind the back platen and heated the nozzle on the area between the platen and the gooseneck. This heating location was not ideal due to the lack of heating that would reach the nozzle-die interface. When undergoing machine testing with zinc before the retrofits it was discovered that the nozzle-die interface did not reach the required temperature for casting, which resulted in solidification at the nozzle-die interface.

3.1.3 Injection System

The AVNET H-35E contained a standard hot chamber injection system consisting of a gooseneck, plunger, pot, and nozzle. The existing system was primarily composed of H-13 components unsuitable for immersion in molten aluminum that the proposed testing required. Previous work was done by Isenberg and FCA to identify and redesign critical components needed to allow for testing with A380.

3.1.3.1 Pot Redesign

Isenberg and FCA formulated a new pot design when envisioning the use of niobium liners in the gooseneck. Accurate dimensional data of the pot did not exist in literature provided to Purdue University. Therefore the pot needed to be sent to FCA for measurement on a coordinate measuring machine (Isenberg 2017, p. 75) A new pot made of cast iron was theorized with a replaceable gooseneck, shown in Figure 3.2.

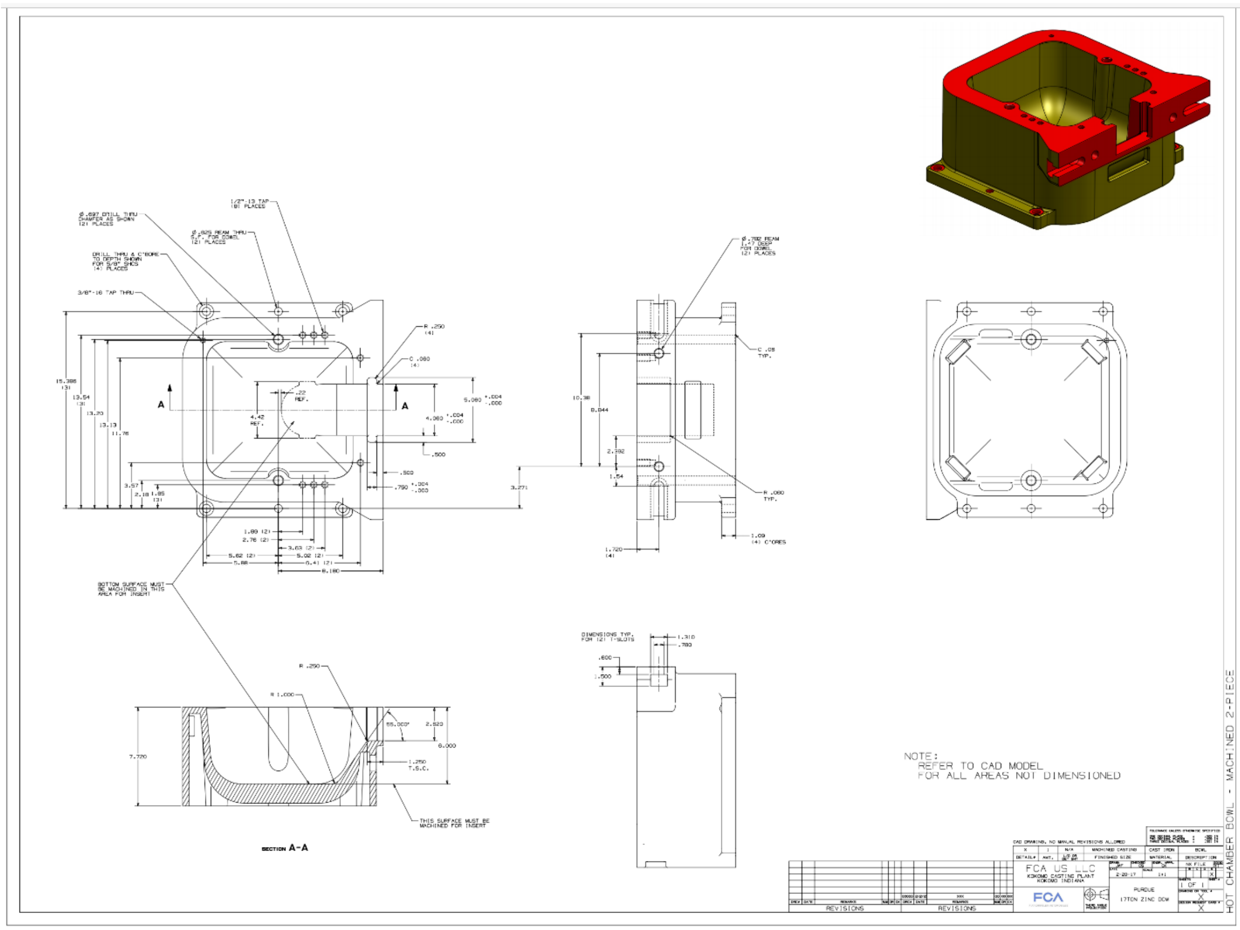

Figure 3.2 Dimensional drawing of redesigned melting pot with replaceable gooseneck

The pot shown was cast by Plymoth foundry and delivered for use in the hot chamber project. Upon installation to the AVNET H-35E multiple sizing discrepancies were found. The holes in the pot mounting flange were found to be undersized and needed to be enlarged. The pot was also oversized vertically, resulting in the nozzle developing a negative angle. The pot was remachined and returned to service. To prevent degredation and premature failure of the pot, boron nitride was applied to separate the molten aluminum to be used from the iron rich cast iron pot.

3.1.3.2 Gooseneck Redesign

Previous project work completed by Isenberg and FCA resulted in redesigned goosenecks designed for rapid replacement. A finished gooseneck can be seen in Figure 3.3

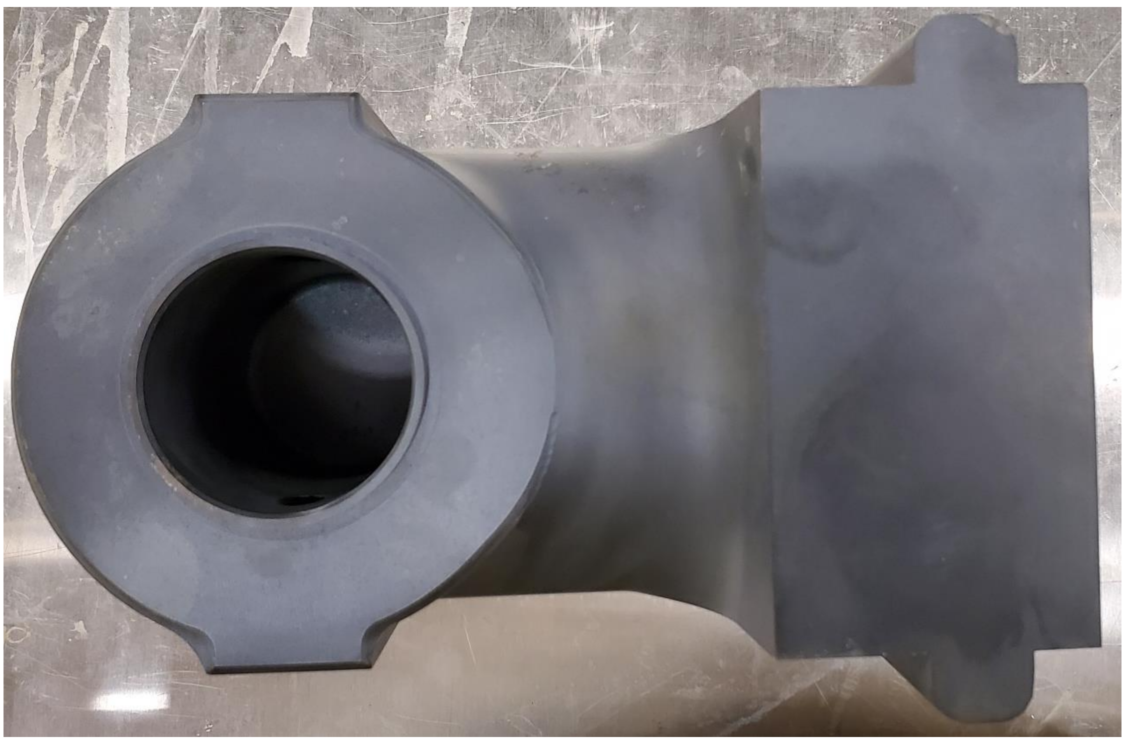

Figure 3.3 Niobium gooseneck redesigned for rapid replacement.

The gooseneck was designed to be replaced in the hopes of decreasing required disassembly to replace test components like the gooseneck shown. “The reason for this was because, although the gooseneck may wear down over time, the melting pot itself should not. Instead of replacing the entire pot, which would mean multiple larger castings of the pot, it would be more advantages to only replace the gooseneck.” (Isenberg, 2017, p.76) The gooseneck being a key test component with its niobium lining this was a key point to consider. The goosenecks were designed to slide in and out of position on the pot for replacement and were mechanically held in place by close tolerances to the pot and the hydraulic shot cylinder's support bracket.

3.1.3.3 Nozzle Redesign

The existing H-13 nozzle provided with the H-35E was made of H-13 steel as seen in Figure 3.4

Figure 3.4 Original H-13 nozzle

With planned retrofits to components suitable for use with aluminum the original H-13 nozzle was identified as unsuitable for continued use. The previous stir tests conducted by Han et. al, as noted by Isenberg showed that using H-13 would lead to both excess iron contamination of the A380 alloy and severe degradation in service life of the current nozzle. A new nozzle needed to be manufactured, and tungsten was identified as the preferred material to be used. During the stir test tungsten suffered relatively low levels of dissolution while at the same time the change from H-13 to tungsten would result in an net increase of temperature at the nozzle-die interface due to the increased thermal conductivity compared to H-13.

3.1.4 Clamping System

The hot chamber die cast machine's configured clamping force was 36.8 tons. The machine tie bars were machined and polished with a diameter of 1.5 inches. Overall tie bar effective length was 46.25 in. Considerable oxidation was noticed on the tie bar sections. Adjustment nuts for platen distancing on the tie bars were seized and immobile. The seizure of the adjustment nuts prevented changes to the die position.

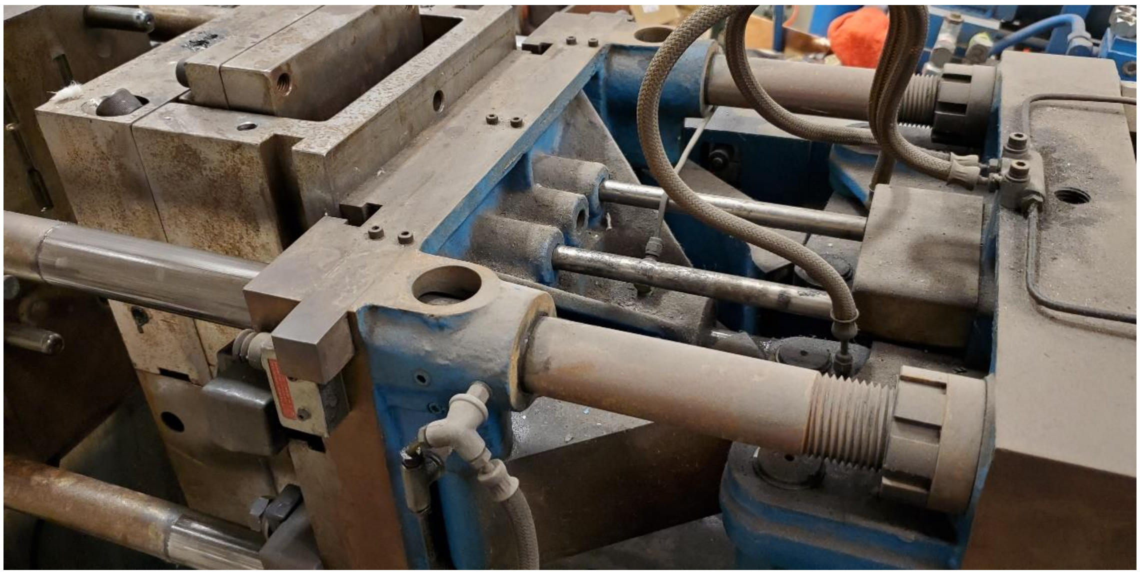

Figure 3.5 AVNET H-35E clamping unit

3.1.5 Dies

When donated to Purdue University by Michigan Technological University, the die cast machine came with a die pre-installed. The die contained a pattern cavity for round tensile specimens along with a simplified gating system designed for molten zinc as seen in Figure 3.6.

Figure 3.6 H-13 die with round tensile bar pattern geometry

The die halves and associated components were constructed of H-13 steel. Each die halve contained two cooling lines, one through the sprue bushing, and the other behind the pattern cavity to facilitate solidification of the casting. Cooling line inside diameters were approximately 0.25 inches. Two tensile samples were able to be created per shot. The fixed die half contained a ZRB-3100 runner bushing to facilitate spherical sealing at the nozzle-die interface while the mobile die half had a matching ZRS-3000 runner spreader. Each die half contained cooling lines which will be expanded upon in the next section.

3.1.6 Cooling System

The existing cooling system of the die cast machine was designed to supply process water (tap water) to three machine components in a single pass system. The first is the heat exchanger on the hydraulic reservoir that facilitated temperature control of the hydraulic fluid throughout the casting process as shown in Figure 3.7.

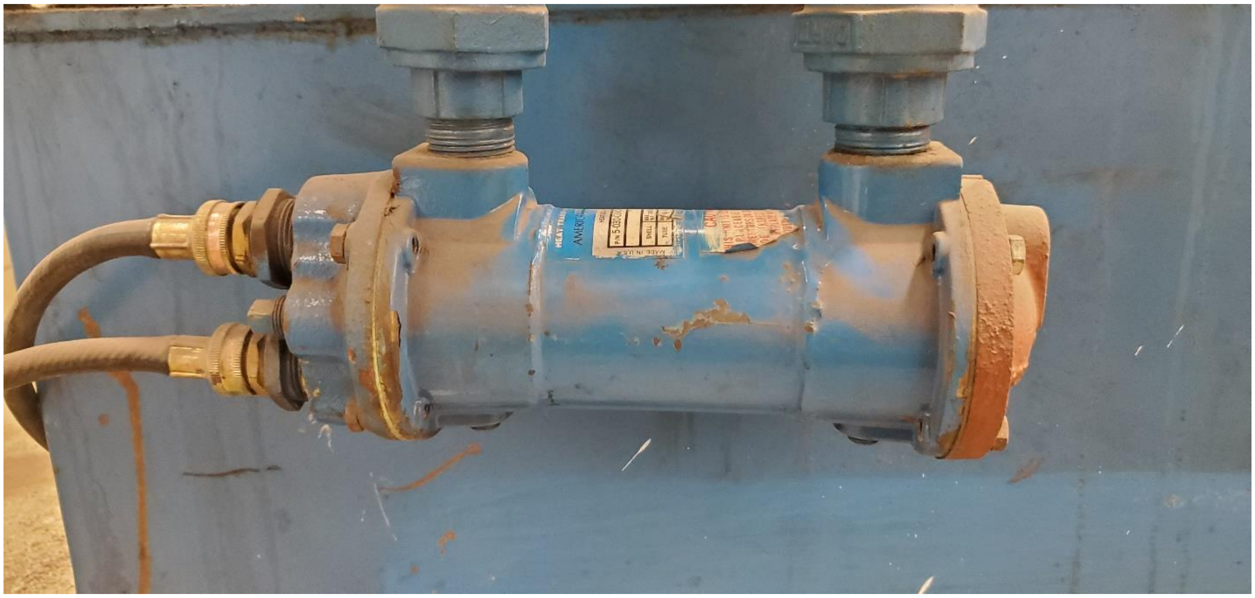

Figure 3.7 Hydraulic fluid heat exchanger.

The single pass heat exchanger was manufactured by American Standard with a part number of 5-030-03-009-003. The maximum temperature rating of the heat exchanger was 300 degrees Fahrenheit.

The second heat exchanger was a plate just below the injection cylinder. The plate was a single pass through in a "U" shape as seen in Figure 3.8.

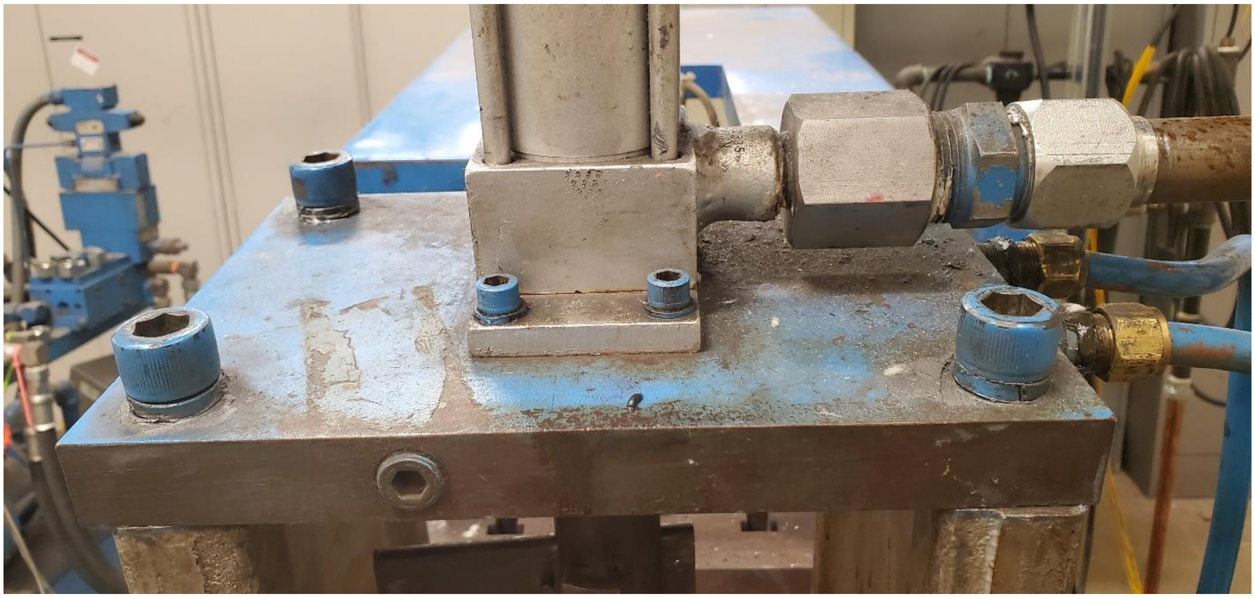

Figure 3.8 Injection cylinder heat exchanger

The hydraulic injection cylinder mounted above the molten metal pot required cooling to prevent overheating and eventual failure of the cylinder. The plate was a custom fabrication specific to the machine, with a pipe inside diameter of 0.500 inches.

The final cooling system consisted of two cooling lines in each of the die halves. One cooling line went directly through each sprue bushing in a single pass configuration. A second cooling line was installed in the upper half of the die, directly behind the part geometry. This cooling line's primary purpose is heat removal to accelerate solidification of cast aluminum.

<u>3.2 Operating Conditions</u>

The AVNET H-35E required an extended startup sequence and heavy preparation before testing began. Gas pressure must be verified and checked to ensure 1.8 psi natural gas pressure is present. The compressed air regulator for the burner was set to 90 psi and pressurized. Nozzle heater temperature setpoints were set to 700 degrees Celsius and the Briskheat temperature controllers set to standby. The melting pot was checked for full boron nitride coverage of the melting pot to prevent aluminum from chemically attacking the cast iron pot. The coating would also prevent iron from being dissolved, changing the iron content of the A380 alloy. The cooling system was pressurized by closing the manifold and opening all upstream shutoffs. Once charged full flow was opened for both the HPU heat exchanger and the heat exchanger for the injection cylinder. The burner was then ignited for furnace heating to commence. Metal can either be melted directly in the pot or ladled from another furnace. The pot was filled with molten metal up to the top of the gooseneck. Time was given to allow for equilibrium to be reached, upon which casting operations began.

3.3 Sample Creation

To create tensile castings, certain process parameters were based off previous simulation work done for this machine and die by Isenberg. Specifically, the alloy was A380, melting pot and gooseneck temperature 620°C and injection speed set to 0.127m/s (Isenberg, 2017, p. 80) Nozzle heater temperatures were set to 700°C. Plunger inject time was set to 3 seconds. Chill timer was set to 10 seconds. Between each casting die lube was applied to thoroughly coat both die halves. After casting the parts were automatically ejected by from the die by way of the ejector pins. Parts were then removed by hand and marked with sample numbers for subsequent testing.

3.4 Sample Tensile Testing

Tensile samples successfully cast were identified and marked at time of casting. Die geometry created round subsize tensile samples as shown in ASTM B557. These samples had an outer grip diameter of 12.7mm, gauge length of 1.000 in, and a diameter of 0.250 inches in the necked section. These samples were tested using a MTS Insight ultimate testing machine configured with a 50 kN load cell and 1 inch axial extensometer. The MTS Insight's grips max work holding diameter was the nominal diameter, 12.7 mm, of the cast tensile bar's grip section. Therefore tensile samples grip areas were turned down to approximately 12.0 mm to ensure adequate grip pressure was applied. Samples were then loaded into the Insight and a 1 inch axial extensometer was attached. Samples then underwent tensile loading until failure by way of constant crosshead speed, 0.050 in/s. Data collected was load, crosshead position, time, and extensometer position. From this data ultimate tensile strength and percent elongation were identified as key mechanical properties. These mechanical properties were compared against recorded data from cold chamber A380 equivalents and similar hot chamber alloys conducted in tests by other researchers.

CHAPTER 4 – RESULTS AND DISCUSSION

4.1 Completed Retrofits

4.1.1 Furnace heating system

The existing natural gas burner of the AVNET H-35E was identified early on during testing of the machine with zinc as being incapable of supporting the increased thermal load necessary for casting aluminum. A new gas burner was identified, an open flame natural gas burner, model 37 from AGF Burner Inc. The burner was rated for 250,000 BTU under normal operation as seen in Figure 4.1.

Figure 4.1 Model 37 open flame burner with pyrometer and pilot light

The existing burner piping system was removed up to mixing valve of natural gas. New piping and fittings were installed to facilitate the new burner piping requirements. Existing pilot light and pyrometer were reused. Upon testing it was noted that the increased burner system still did not have enough energy potential to maintain adequate temperature for a full pot of molten aluminum as is required for gooseneck immersion and machine operation. This was due to the large amount of surface contact and corresponding heat loss to the machine frame, platens, tie bars, and die itself. High temperature thermal wool was applied to the exterior and top of the melting pot, platen, and fixed die half in an attempt to limit thermal losses. The thermal wool application proved to be effective, even more so as added insulation facilitated heat transfer into the fixed die half through the platen and nozzle. Doing so allowed for the preheating of the die half and increased nozzle temperature stability.

4.1.2 Nozzle Heating System

The original nozzle heating system of the AVNET H-35E consisted of a natural gas and compressed air torch. The torch was aimed at the nozzle, with the flame contacting it behind the platen. When undergoing tests with zinc nozzle blockage was observed at the nozzle-die interface due to insufficient preheating of the interface. Knowing this two paths were undertaken. An anviloy nozzle, composed primarily of tungsten, was used to replace the existing H-13 nozzle. The anviloy nozzle allowed for better thermal conductivity from the melting pot and furnace to the nozzle-die interface. Along with this, two electric nozzle heaters were procured along with a power supply and temperature controller. Figure 4.2 shows the new nozzle heater, while Figure 4.3 shows the new temperature controller.

Figure 4.2 New Watlow band heater

Figure 4.3 New Briskheat band heater power supply and temperature control unit

The mica insulated heaters were supplied by Watlow and operated at 1000W, 240V. The heaters had an approximate inside diameter of two inches, with a two inch width. One was set between the fixed die and the platen while the other was positioned between the platen and the melting pot. The heaters were configured for type K thermocouples as were the PID controllers in the Briskheat controller. The electric heaters performed phenomenally. Nozzle operational temperatures were easily maintained in areas directly underneath the heaters. Combined with the increased thermal conductivity of the anviloy nozzle the nozzle-die interface saw significant temperature increases. When combined with sufficient preheating of the dies and platen sufficient temperatures at the nozzle-die interface were reached to facilitate casting.

4.1.3 Injection system

The new pot, niobium gooseneck, and plunger setup is shown in Figure 4.4.

Figure 4.4 Hot chamber injection unit with niobium gooseneck installed

This setup was designed to test the longevity and effectiveness of new shot components in the hot chamber process. Extensive misalignment was noted in the injection system, directly related to manufacturing and measurement defects during production.

4.1.4 Cooling system

The upgraded cooling manifold and other cooling systems operated as expected. Effective cooling was applied to both the die, HPU, and injection heat exchanger. Standard single pass water proved effective at regulating the component temperatures. Precise control was established with the use of needle valve flow controls as seen in Figure 4.5

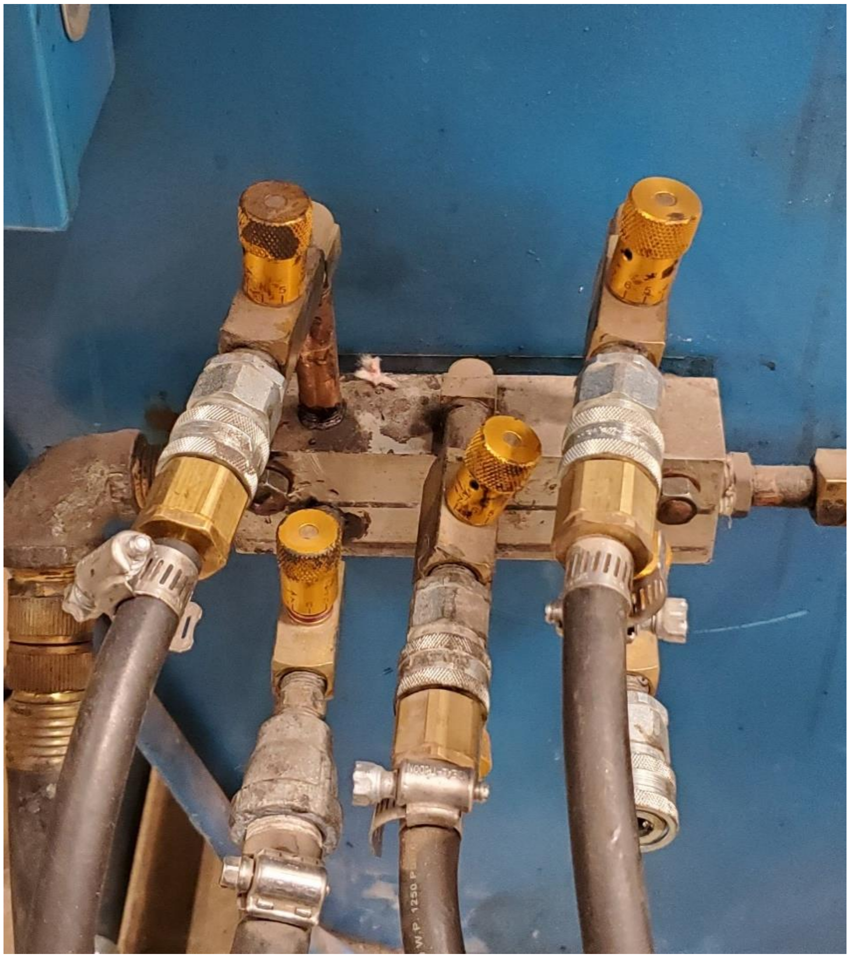

Figure 4.5 Upgraded die cooling manifold

4.2 Nozzle – die interface

The nozzle-die interface sealing proved to be problematic during testing. Given the number of components replaced in the shot end, such as the gooseneck, pot, and nozzle, mechanical alignment between the die and nozzle was lost. The new anviloy nozzle also proved to be slightly shorter than the original H-13 nozzle, leading to a gap between the nozzle and die sprue bushing. The gap lead to molten metal leakage at the nozzle-die interface, shown in Figure 4.6.

Figure 4.6 Nozzle heater encasement in aluminum due to nozzle-die interface leak

Upon further investigation multiple factors were noticed to contribute to the leakage. The angle of the nozzle in the new gooseneck and pot did not align properly with the platen angle. The effective length of the nozzle had changed, leading to a gap between the nozzle and die bushing. Eventually sealing was obtained by the addition of a copper crush washer between the nozzle and die bushing.

4.3 Gooseneck and Plunger Failure

After 12 heating and cooling cycles, the injection system by way of the gooseneck failed. The gooseneck exhibited severe signs of oxidation on areas exposed to atmosphere as seen in Figure 4.7. As seen in Figure 4.7, there is significant soldering of aluminum to the H-23 plunger.

Figure 4.7 Niobium gooseneck oxidation

The injection system began to exhibit signs of failure during the eighth testing run. Extensive oxidation was noted, along with small amounts of aluminum escaping through the seal between gooseneck and plunger. Upon further testing cycles gooseneck blow by increased. Ultimately on the 12^{th} cycle the plunger seized in the gooseneck. The plunger was unable to be removed by both manual hand leverage and hydraulic pressure applied by the injection cylinder.

Given the amount of niobium oxidation observed through testing cycles it is theorized that dimensional tolerancing was lost due to this oxide formation. Extensive soldering can also be seen on the H-23 plunger, particularly at the top of the upper edge of the gooseneck.

4.4 A380 Tensile Sample Mechanical Properties

Seven viable tensile samples were created throughout the project. These samples were tested using an MTS Insight tensile tester. This testing machine was configured with a 50 kN load cell and 1 inch axial extensometer. Samples were tested under tension and data recorded for review as seen in table 4.1. Multiple defects were seen in all samples, leading to much lower ultimate tensile strength than expected.

Table 4.1 A380 Hot chamber testing results

Sample # (A380 Alloy)	UTS (psi)	Elongation (%)
Sample 1	7110.208	1.106
Sample 2	7542.408	1.203
Sample 3	6535.656	0.9266
Sample 4	3231.21	0.168
Sample 5	5203.644	0.6212
Sample 7	3196.407	0.2369
Sample 8	4960.074	0.5644

CHAPTER 5 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

A older hot chamber die cast machine, for example a AVNET H-35E, was reconfigured and retrofitted for use with molten aluminum. The work required the redesign and replacement of many components on the shot end such as the nozzle, gooseneck, plunger, and pot. Several new components were remanufactured for use with molten aluminum and suffered dimensional tolerancing issues due to insufficient documentation or measurement errors during reverse engineering. The dimensional tolerancing issues along with other existing mechanical issues lead to extensive molten metal leakage at the nozzle-die interface. Nozzle-die interface sealing was eventually established through the use of a copper plate acting as a crush washer. Subsequently seven aluminum samples were created and tested for ultimate tensile strength and elongation. Further sample creation was impossible due to seizure of the plunger inside the gooseneck due to extensive niobium oxidation and galling of the H-23 plunger and rings. Mechanical properties of the A380 samples created through the hot chamber process proved to be extremely poor. Defects were noted in every sample, ranging from oxide inclusions to porosity.

5.2 Conclusion

The study has proved that an aluminum hot chamber machine is possible. However multiple machine systems did not work to their full potential, leading to extensive rework and subpar mechanical properties of cast samples. Machine failures, such as leakage at the nozzle-die interface and improper gating design of the die suggested that the A380 tensile results not be taken as indicators of process viability.

5.3 Recommendations

Future development of this system is highly recommended. Numerous design issues with the existing system, have been identified. To begin, rework of the nozzle-die interface is critical. Recommended work includes that a new sprue bushing be created or procured to better facilitate a seal at the interface. Sealing of the nozzle-die interface would most likely be accomplished through machining of the bushing to account for the angular and dimensional changes in nozzle position that occurred during redesign and machining of the goosenecks and melting pot. A new heating system for the molten metal holding pot is also recommended. The retrofitted gas burner system resulted in sufficient melting and holding capacity of molten metal to operate the machine but also resulted in heavy point heating of the pot directly under the gooseneck. A more distributed gas system, or ideally an induction system would result in better temperature conformity of the melt and melting pot while eliminating potential risks to the gooseneck by overheating.

LIST OF REFERENCES

Ahamed, A. K., & Kato, H. (2008). Influence of Casting Defects on Tensile Properties of ADC12 Aluminum Alloy Die-Castings. *MATERIALS TRANSACTIONS*, *49*(7), 1621–1628. https://doi.org/10.2320/matertrans.f-mra2008814

ASTM International. (2018). *B393-18 Standard Specification for Niobium and Niobium Alloy Strip, Sheet, and Plate*. Retrieved from https://doi-org.ezproxy.lib.purdue.edu/10.1520/B0393-18

ASTM International. (2015). *B557-15 Standard Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products*. Retrieved from https://doi-org.ezproxy.lib.purdue.edu/10.1520/B0557-15

ASTM International. (2018). *B85/B85M-18e1 Standard Specification for Aluminum-Alloy Die Castings*. Retrieved from https://doi-org.ezproxy.lib.purdue.edu/10.1520/B0085_B0085M-18E01

Butler, W. (2008). High-Pressure Die Casting. In *ASM handbook: casting* (Vol. 15, pp. 715–718). ASM International. https://doi.org/10.31399/asm.hb.v15.9781627081870

Chicago White Metal Casting, Inc. (2021). *Cold Chamber Die Casting Diagram*. Hot Chamber vs. Cold Chamber Die Casting. https://cwmdiecast.com/2016/05/27/die-casting-101-hot-chamber-vs-cold-chamber/.

Davis, J. R. (1995). Selection of Materials for Die-Casting Dies. In *Tool materials* (p. 251). Materials Park, OH: ASM International.

DYNACAST. (2021). *Operating sequence of the cold chamber die casting process.* Cold Chamber Die Casting. https://www.dynacast.com/en/specialty-die-casting/die-cast-process/cold-chamber-die-casting.

DYNACAST. (2021). *The Components of The Hot Chamber Die Casting Machine*. Hot Chamber Die Casting. https://www.dynacast.com/en/specialty-die-casting/die-cast-process/hot-chamber-die-casting.

Fiorese, E., & Bonollo, F. (2016). Plunger Kinematic Parameters Affecting Quality of High-Pressure Die-Cast Aluminum Alloys: Physical Metallurgical and Materials Science. *Metallurgical and Materials Transactions, 47*(7), 3731-3743. http://dx.doi.org/10.1007/s11661-016-3522-7

Han, Q., Vian, C., & Good, J. (2020). Application of refractory metals to FACILITATE Hot Chamber aluminum die casting. *International Journal of Metalcasting*. doi:10.1007/s40962-020-00482-7

Isenberg, D. (2017). *Hot Chamber Die Casting* (Publication No. 10607266) [Master's Thesis, Purdue University], ProQuest Dissertations Publishing.

McInerney II, R. (2008). High-Pressure Die Casting. In *ASM handbook: casting* (Vol. 15, pp. 724–726). ASM International. https://doi.org/10.31399/asm.hb.v15.a0005266

Okayasu, M., Yoshifuji, S., Mizuno, M., Hitomi, M., & Yamazaki, H. (2009). Comparison of mechanical properties of die cast aluminium alloys: cold v. hot chamber die casting and high v.low speed filling die casting. *International Journal of Cast Metals Research*, *22*(5), 374–381. https://doi.org/10.1179/174313309x380413

The Library of Manufacturing. (n.d.). *Cold Chamber Die Casting Machine (Top View)*. Cold Die Casting. http://thelibraryofmanufacturing.com/cold_chamber_diecasting.html.