

ADVANCED MANUFACTURING TECHNOLOGY

Assessment 1

ENME804

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1 Introduction to MAM methods

Additive Manufacturing, or more commonly known as "3D printing" is a process where a 3 dimensional object is printed layer by layer on a 3D printer. The material can be polymer or metal. Most consumer grade 3D printers are for use with polymers such as PLA, PETG or ABS.

Some major Metal Additive Manufacturing(MAM) methods include Powder Bed Fusion, Direct Energy Deposition which has Powder Feed and Wire Feed MAM systems. However, Powder Bed Fusion is the most common method for metal 3D printing. There are two melting techniques: Selective Laser Melting and Electron Beam Melting.

2 Powder Bed Fusion

Powder Bed Fusion is printed on a bed of metal powder. Either a roller or a hopper distributes the powder onto the build chamber. The laser or electron beam then melts the metal powder on the build chamber. The build chamber moves down and the roller makes another pass, which signifies the next layer. The process is repeated layer by layer until the build is complete.

2.0.1 Selective Laser Melting

The delivery system on an SLM machine drops the powder into the left side cavity then a roller rakes it onto the build platform. SLM build chamber is sealed and relies on a mirror to direct the laser down onto the build platform to melt the metal powder. After printing on the SLM, the excess metal powder can either be brushed off or vacuumed away, though SLM parts have supports and stresses that need a post heat treatment unlike the EBM. The accuracy of SLM depends on the laser beam, its diameter, routing and layer height. Another disadvantage is a longer print time.

- Slow because powder is layered on with a rake roller
- Produces the parts with small high powered laser
- Typically build volume is smaller because the chamber is filled with inert gas to prevent oxidation
- Powder size 20 – 63 μ m
- Surface finish is rough and may need post processing
- Needs supports
- Large range of metals available

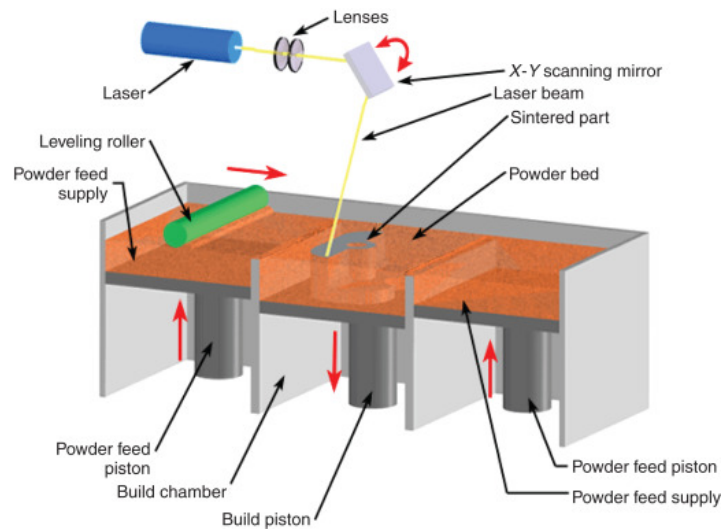


Figure 1: Schematic of SLM process [3]

2.0.2 Electron Beam Melting

The delivery system of the EBM occurs from the hoppers on either side of the build platform, the metal powder is then raked onto the build plate then a powerful electron beam heats and melts the powder, first contour melting then hatch melting. An example of EBM is General Electric's Arcam EBM. The build chamber inside this machine is vacuum sealed to ensure a clean and controlled environment which allows for the processing of reactive material. The electron beam unit has no moving parts which allows for fast and accurate beam control. A disadvantage of EBM is that it can only be used with a limited amount of metals currently [7], one of which is Titanium alloy. This technique is mainly used to produce parts for the aerospace industry.

- The speed of production is an advantage of the EBM. The electron beam can heat the metal powder on the bed simultaneously in multiple places which speeds up the production. For SLM, a laser must scan the bed from point to point
- Because EBM heats the metal powder on the bed before the beam melts anything, this limits any deformations and reduces and even eliminates the need for reinforcements and supports during manufacturing
- Powder size $45 - 105\mu m$
- High power compared to SLM
- Vacuum chamber
- EBM lacks in precision because the electron beam is wider than the SLM laser beam, this reduces the accuracy of the EBM
- Another disadvantage is the build volume. SLM machines are able to manufacture volumes twice as high as the EBM machine

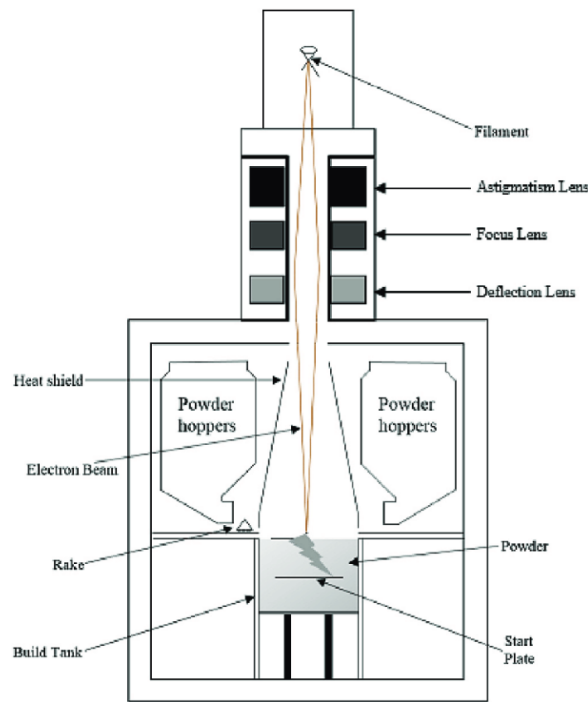


Figure 2: Schematic of Arcam EBM [4]

	SLM	EBM
Melting Point	Below melting point	Above melting point
Materials	All materials	Titanium Alloys
Type of beam	Laser beam	Electron beam
Energy Saving	**	***
Melting Ratio	Partial	Fully
Build Temperature	~200°C	680+°C
Sealed Chamber	Inert gas (Argon)	Vacuum
Supports	Yes	No

Table 1: Comparison of SLM and EBM [6]

2.1 Direct Energy Deposition

2.1.1 Powder Feed System

Powder Feed MAM system (Powder DED) or "Laser Metal Deposition (LMD)" technique is used. Instead of spreading metal powder over the build platform, metal powder is fed through the print head and accurately blown onto a part with the on head laser fusing it simultaneously. Powder Feed systems are quite similar to SLM as they both use metal powder and lasers to print however, because of how the powder is distributed, it can fix defects in prints that haven't yet been printed. The parts produced by Powder Feed systems are very similar to SLM printed parts.

- Fast because of hopper dropping material
- Produces fine parts with electron beam
- Build volume is usually small because the chamber is vacuum sealed to prevent oxidation and electronegative charging

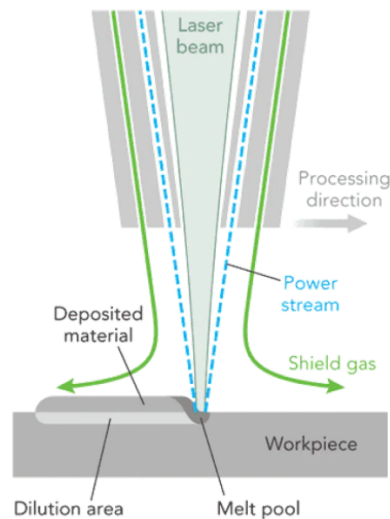


Figure 3: Schematic of Laser Metal Deposition process [1]

2.1.2 Wire Feed System

Wire Directed Energy Deposition system, or Electron Beam Additive Manufacturing (EBAM) is very similar to Powder DED where they also use a laser to melt the feedstock however this time the feedstock is a wire instead of metal powder. Wire DED are usually used with larger build volumes (as large as 5m x 1m x 1m). They print faster compared to powdered bed but compromises the print quality and accuracy. Due to this, parts are designed to be larger and less accurate than powdered bed machines. They may be good for rapid prototyping but not good for rapid prototyping of optimised precise parts.

- Slow/medium because solid wire is applied and melted
- Resolution typically limited by the wire extension so big parts are best for this method
- Build volume is not as restricted as other methods and can produce bigger parts

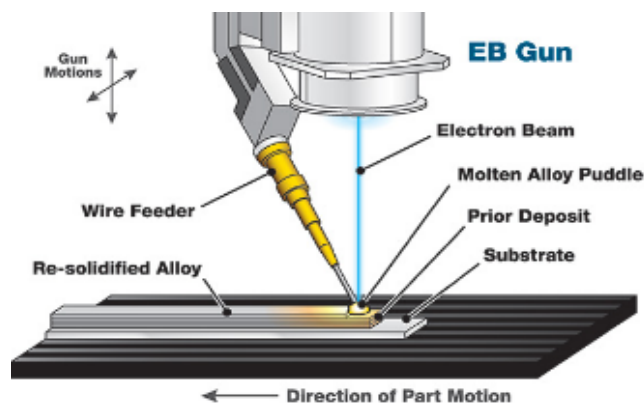


Figure 4: Schematic of Electron Beam Additive Manufacturing process[2]

3 Energy generation and transfer

3.1 Laser Powder Bed Fusion

As seen in Figure 1 on Page 3, the schematic shows an SLM machine. The energy is generated from the CO₂ laser and shone through the lenses and directed down into the build platform via an X-Y scanning mirror. The heat from the laser melts the metal powder fuses and hardens it. The powder feed piston moves the powder feed supply up which means the levelling roller can make another pass over the build platform giving it another new layer. The chamber in the SLM is sealed and is sometimes filled with an inert gas such as Argon to maintain atmosphere, prevent oxidation, minimise contamination due to high temperature processing and to remove condensation, which can reduce the effectiveness of the laser reaching the powder bed through absorption.

3.2 Election Beam Powder Bed Fusion

The main difference between EBM and LPBF is the type of beam used. The electron beam is produced by an electron gun. It "Extracts the electrons from a tungsten filament under vacuum and projects them in an accelerated way on the layer of metallic powder deposited on the building plate of the 3D printer and is controlled by two magnetic coils for focusing and controlling the position and diameter of the beam. These electrons will then be able to selectively fuse the powder and thus produce the part." [7] In order for the electron beam to operate properly it must be under vacuum conditions. This also prevents the produced part from oxidizing when heated. Because this technique is based off electrical charges, only conductive materials may be used so materials such as ceramics or polymers will have no effect under an electron beam.

4 Surface features and major forms of internal defects

Although powder bed fusion is quite popular, its major drawback is the low surface quality. "Weld" tracks with weld tear drop appearance and weld splatters can be observed on a printed part [8].

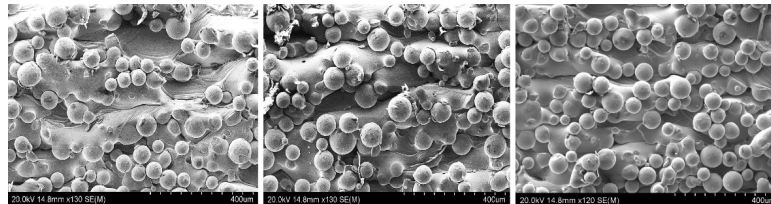


Figure 5: "Weld" tracks seen under microscope[8]

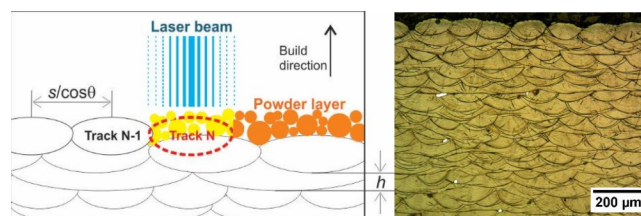


Figure 6: Cross section showing multiple tracks[8]

Lack of fusion can occur when there is not enough power or laser intensity is too low causing the metal not to fuse properly. When too much power is used, hot cracking occurs.

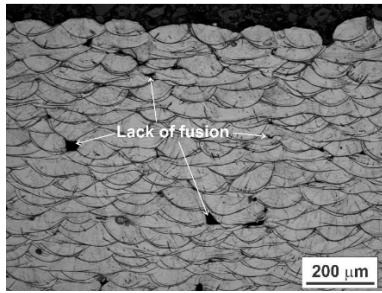


Figure 7: Lack of Fusion between tracks[8]

Lack of Fusion can be reduced by controlling the following:

P = Laser Power

ν = Scan speed

s = Track spacing

h = Layer thickness

$$E = \frac{P}{\nu \cdot s \cdot h} [10] \quad (1)$$

Hot cracking occurs when the temperature nears the solidus of the metal where it has coherence but is brittle and can be found on the longitudinal axis and can appear on other directions as it is affected by tensile stress.

The metal becomes brittle due to dendritic grain growth along the build direction

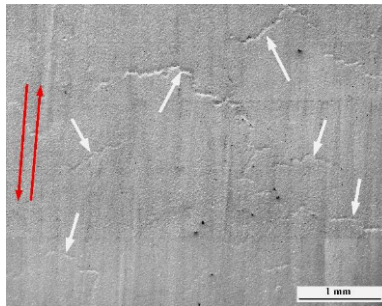


Figure 8: Hot cracking along grain boundary[8]

5 Introduction on die casting

5.1 Operational principle, pressure supply control and process capability

5.1.1 Low Pressure Die Casting

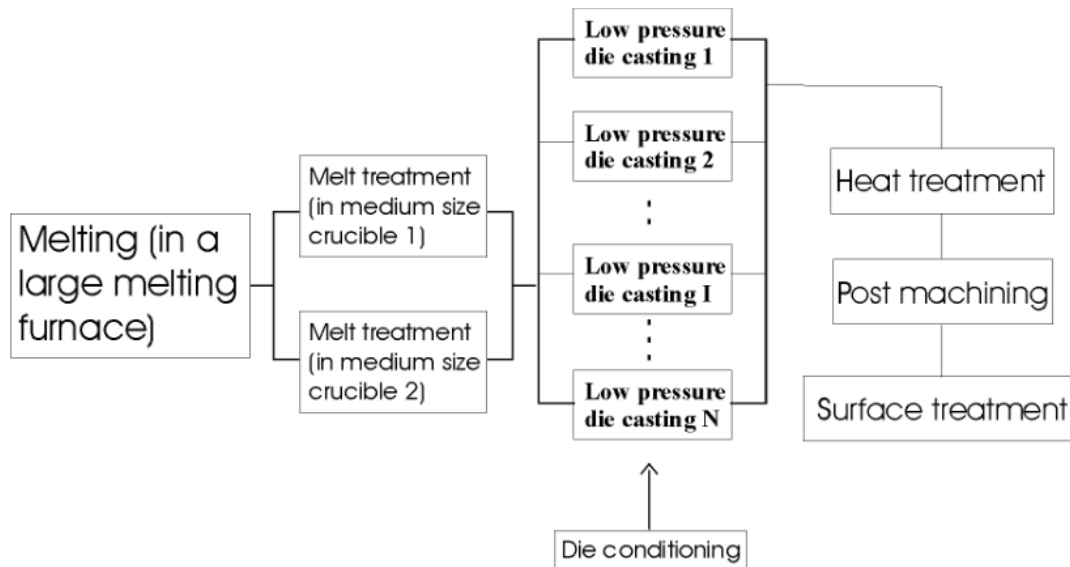


Figure 9: LPDC steps in manufacturing aluminium alloy components [8]

The LPDC process begins with a sealed furnace with molten metal. The molten metal is forced to go up the tube into the die cavity - this is done by increasing air pressure inside the furnace. Dependent on what flow velocity is required, the air pressure can be adjusted to achieve that. After filling the die cavity, pressure is increased and maintained until it has solidified. The max pressure can reach up to 50KPa which is much lower than the pressure applied in the HPDC process which is why this is called 'Low Pressure Die Casting.' To finish the process, the pressure in the furnace is reduced or released, this makes sure any excess liquid alloy falls back into the furnace or down the riser tube. The die is then opened the casting is taken out. LPDC has precise control of die cavity filling, usually used to manufacture axially symmetrical parts such as an aluminium car wheel or beer barrels.

One of the major problems in LPDC is the generation of micro pores. There are two types of micro pores: gas pores and shrinkage pores. Gas porosity is generally caused by Hydrogen in Aluminium alloys. Equation 1 shows the chemical reaction of Hydrogen dissolving into Aluminium alloy [8]

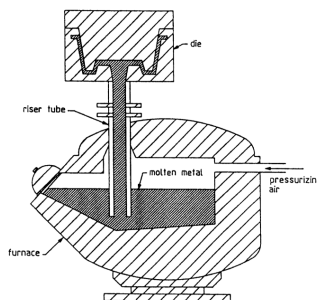


Figure 10: Schematic of a LPDC machine [8]

5.1.2 High Pressure Die Casting

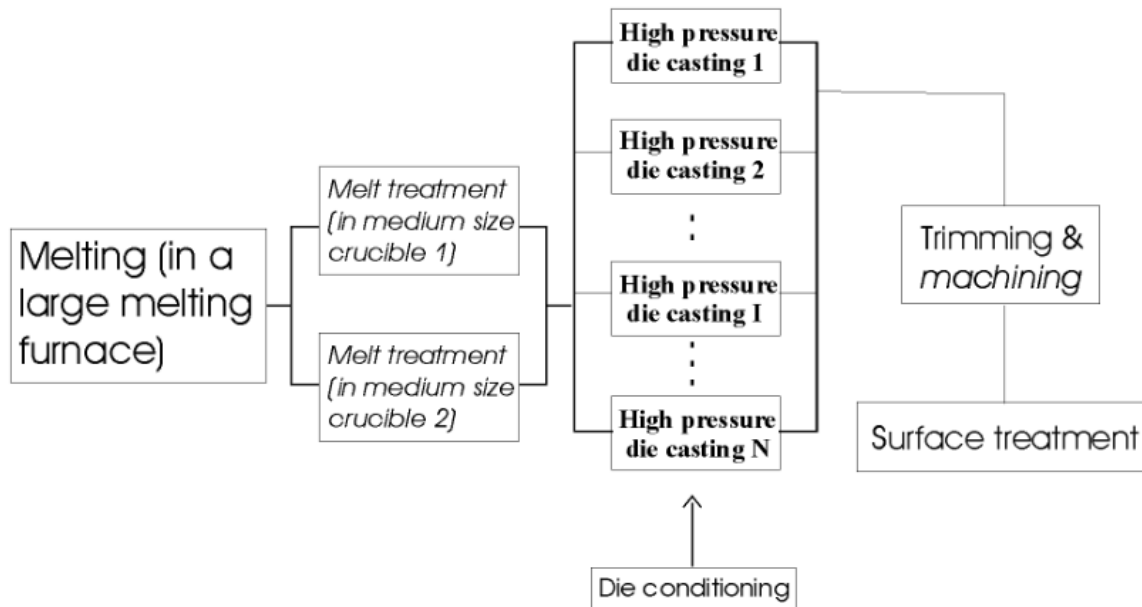


Figure 11: HPDC process in manufacturing aluminium alloy components [8]

High pressure die casting uses a cold chamber die casting machine which is shown in Figure 7. This machine uses a system which provides hydraulic power which controls piston position, velocity and acceleration when filling the die cavity. From shot sleeve via runner and gate and finally into die cavity. After filling the die cavity, a high pressure of around 69MPa is applied through the piston - this is called "Pressure Intensification." Because of this pressure intensification, the force required to open the die will be quite high (dependent on area, runner and gating). This is also the force that is required to keep the die closed.

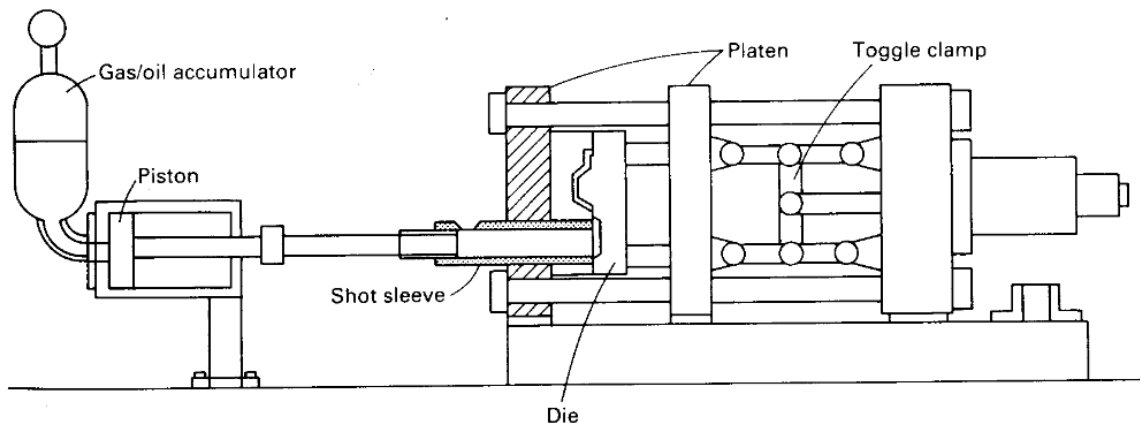


Figure 12: Schematic of a HPDC cold chamber machine [8]

This is a typical high pressure die casting cycle:

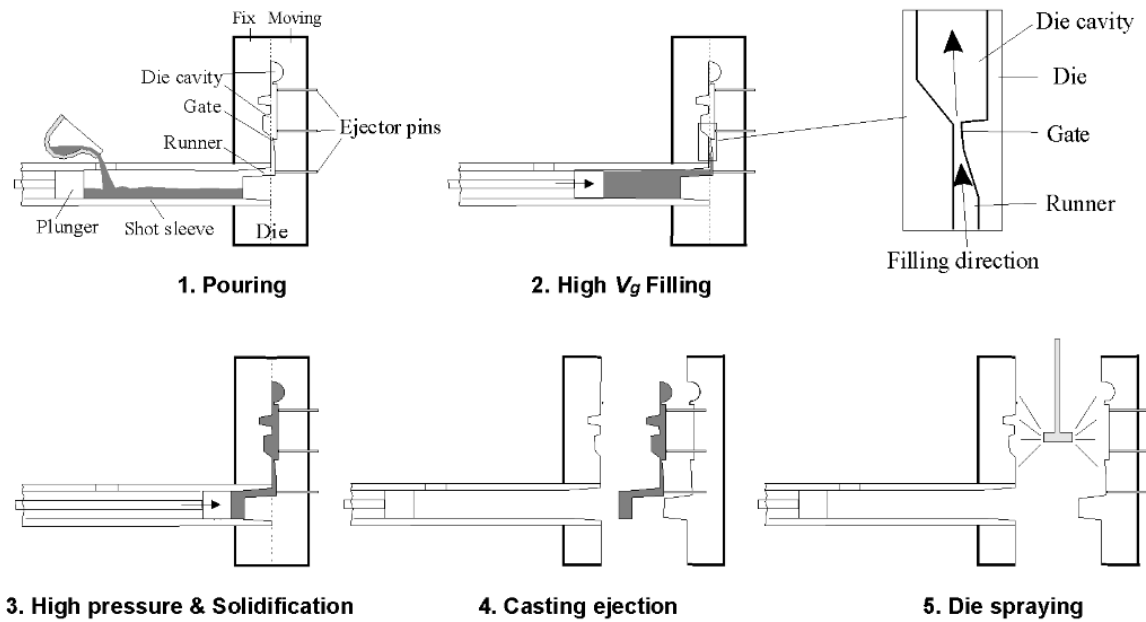


Figure 13: High pressure die casting cycle [8]

- 1) Molten metal is taken from the furnace and poured into shot sleeve
- 2) Pushing the plunger in shot sleeve to fill the die cavity with the molten metal
- 3) Pressure intensification is applied while it solidifies
- 4) Once cooled, die is open to retrieve the part
- 5) A mixture of water and lube is sprayed onto die in preparation for the next build

In stage 2 of the cycle, the force pushing the plunger $V_g = 0.1$ m/s for a non turbulent flow which also displaces the air into the runner, preventing air entrapment (porosity).

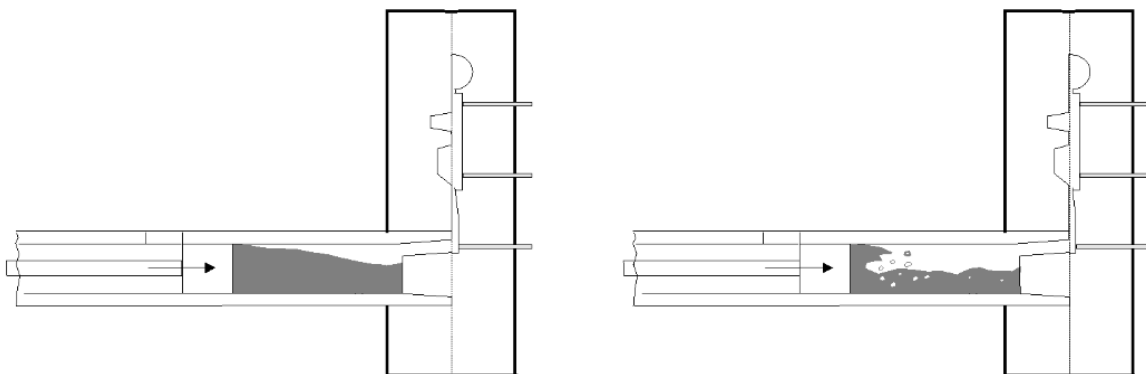


Figure 14: Stage 2 of the cycle [8]

The left hand side shows an initial slow filling process with no air trapped with the liquid metal and has laminar flow. However the right hand side shows an initial uncontrolled fast filling from the plunger which causes the liquid metal to be turbulent and trapping air which causes porosity. It then transitions to a higher velocity after the shot sleeve is filled completely to $V_g = 2$ m/s. The thin gates used (ranging from 2-4mm) makes it easy to trim post casting but because the gates used are thin, which causes V_g to be high when exiting, around 40-60 m/s.

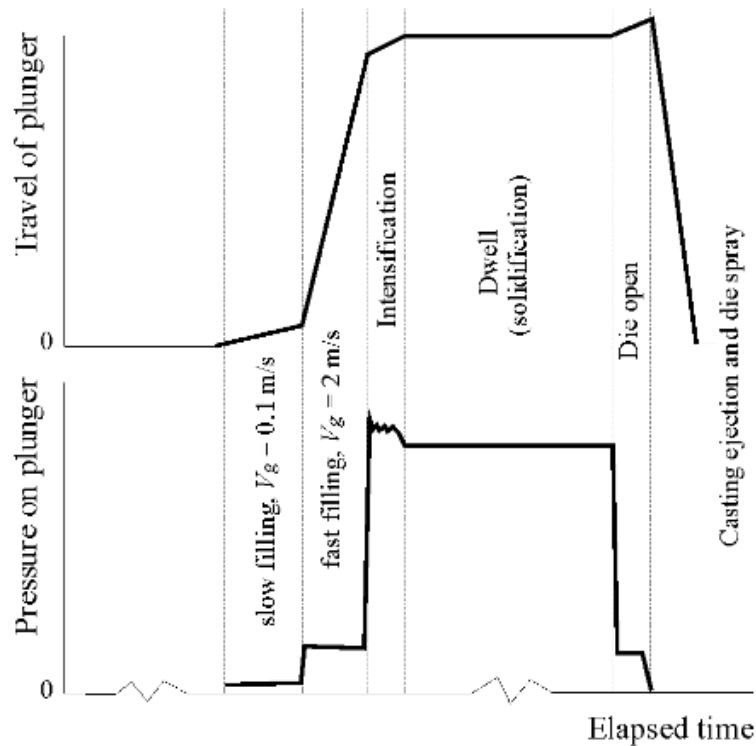


Figure 15: Travel against Time and Pressure against Time [8]

High pressure die casting can produce parts that are thin and complex with high accuracy and above average surface finish, also has a high production rate. This is due to two features: "Fluidity" and "Squeeze Capability." Fluidity is defined as "the maximum distance to which the metal will flow in a standard mould" so a high rate of filling will minimise premature solidification. On top of this, after the initial slow filling process, it transitions to fast filling, as seen in Figure 10, a high pressure is applied squeezing as much liquid into the die cavity as it can, making sure there are no air pockets. HPDC is high capable of producing highly complex shapes, examples of which include automatic transmission cases and pump cover.

Although HPDC is used quite a lot in manufacturing, it is not capable of producing parts for structural purposes, only net shaped parts. This is due to multiple reasons: Turbulent flow and gas porosity, insufficient feeding and shrinkage porosity.

In Figure 9, the diagram on the right hand side shows what happens with a high filling velocity during filling, which is turbulent flow. When $V_g = 40-60$ m/s, the liquid metal splashback causes bubbles. A better design of the gate thickness or shape can optimise filling of the die and use of vents to expel gas though one thing commonly found in HPDC are a large amount of porosity. The large amount of porosity reduces the strength of the component and when it reaches the the stage of "Pressure Intensification," the air bubbles get compressed. If this is then heat treated, the air bubbles would expand and pop, causing long lasting blisters like popping a pimple would leave a scar on the face. Because it is not heat treatable, the strengths are usually low, around "100MPa for an as-cast aluminium alloy compared to over 200MPa if the alloy could be treated"[8]

Between stage 2 and 3 from Figure 8, during solidification, shrinkage happens during "Pressure Intensification," this can be dealt with by forced feeding. Because of the thin gates for post trimming, the gates solidifies before the cast in the die. Because of this, when the die cavity has solidified shrinkage, no more liquid metal could be fed therefore shrinkage pores are usually found in the interior of the cast.

5.1.3 Squeeze Casting

Squeeze casting overcomes the disadvantages that HPDC has which are highly turbulent flow during die cavity filling and insufficient feeding during solidification which causes formation of micro porosity.

Molten metal is transferred from the melt into a ladle and poured into a shot sleeve with a piston. The shot sleeve then docks vertically underneath the die cavity. Then the molten metal from the shot sleeve is injected into the die cavity (Vertical Injection Squeeze Casting), this eliminates any turbulent flow in the shot sleeve compared to HPDC horizontal shot sleeve. This is a method by which molten alloy is cast without turbulence or gas entrapment at high pressure to yield high quality, dense and heat treatable parts. "The characteristic of squeeze casting are its slow filling and solidification under squeeze pressure up to 100MPa." [8]

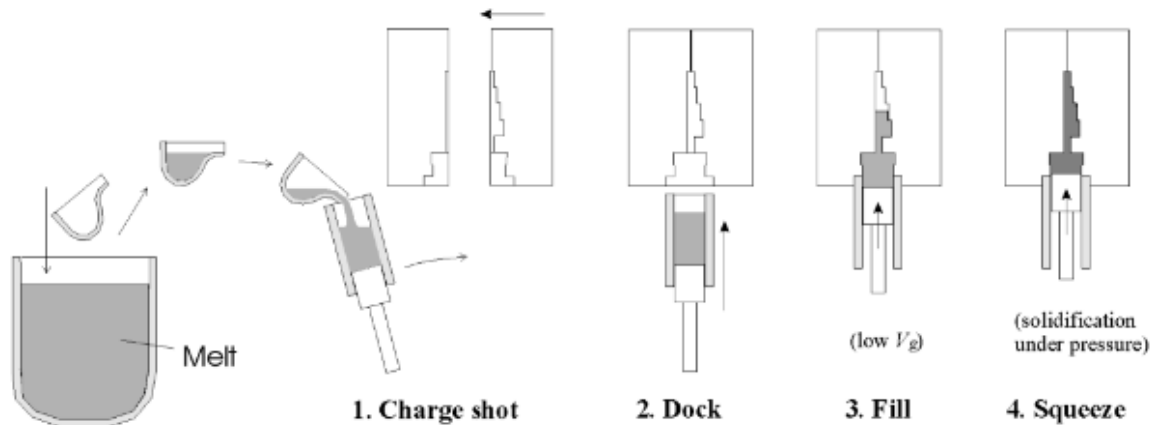


Figure 16: Schematic of Squeeze casting process [8]

Squeeze casting machines are very similar to HPDC machines so its capability to manufacture complex parts is the same. With a few modifications to the die design and filling velocity, an HPDC machine can be used for squeeze casting. An example of this is HPDC uses a horizontal shot sleeve whereas Squeeze cast uses a vertical shot sleeve and slow filling velocity.

5.2 Minimising defect formation

5.2.1 Low Pressure Die Casting

Filling velocity and flow path will need to be considered in order to achieve high quality castings which have a low rate of rejection and less amount of post machining. A low filling velocity means it is less likely to have turbulent flow and surface instabilities. The filling velocity also cannot be too low because that would result in heat loss and premature solidification resulting in die cavity not being able to be filled.

As stated in Page 9, flow velocity is dependent on air pressure in the furnace. Usually air pressure is toggled to allow liquid metal to smoothly fill the die cavity. Though "many casting experiments have shown that when metal front velocity is higher than 0.5 m/s, the liquid metal front would become unstable, causing entrapped air bubbles and generating oxides in the casting." [8] Oxidation and porosity reduce the overall strength and mechanical properties of the material.

If the liquid metal fails to fill the die cavity completely due to premature solidification then it is not considered to be "fluid." "Fluid" is defined as "the maximum distance to which the metal will flow in a standard mould." [8] It is a relative measure of filling capacity. To prevent premature solidification in LPDC, the mould would need to be kept at high temperatures and also apply an insulating coat. "It is very clear that a higher filling velocity could be used to better fill the casting, particularly for large castings of a complex shape. Flow velocity needs to be lower than critical value to avoid flow turbulence and surface instabilities. To avoid premature solidification and lack of fill, thicker castings are often the solution." [8]

When the liquid metal starts solidifying, the pressure changes making the pressure difference between interior and exterior to increase. This is what causes the growth of pores but is also why various feeding mechanisms are used to reduce this. As stated in Page 24 of the Slides [8], Campbell described 5 mechanisms where solidification shrinkage can be fed. To minimise defect formation, the mould would also need to be carefully designed to allow for liquid feeding and also the routing for the liquid. Along with a carefully designed die, thermal control of the die is also needed so that solidification can be directional, as far up as possible in the riser tube.

5.2.2 High Pressure Die Casting

High Pressure Die Casting Dies are subjected to severe conditions in their lifetime. These include:

- 1) Mechanical impact and wear
- 2) Fatigue loading caused by thermal cycling
- 3) Low strength due to exposure of high temperature for long periods
- 4) Metallurgical reactions between die and cast alloys (Soldering)

Fatigue caused by thermal cycling and Soldering are the two major common failure modes.

The die surface is often exposed to extreme temperatures and rapid changes of temperature. It also encounters thermal shock. The temperatures range from very high at the beginning when metal is in liquid form to the very end when it gets sprayed and temperature is at the lowest. The rapid changes result in tensile stress at the surface of the die especially when it gets sprayed which means that it undergoes thermal fatigue.

Metallurgical reactions between die and cast alloys is called soldering. It causes the die cast to stick. Not only does this damage the die surface but also causes the cast to become defective. The longer the die is exposed to high temperatures, the more likely for it to stick. One way to reduce this is to cool locally, although using an inert coating may be more effective. The use of a thin gate causes jetting, by applying a high force over a small cross sectional opening, the flow becomes turbulent and causes gas bubbles. When heat treated, the gases expand and causes rough surface finish and poor mechanical properties.

5.2.3 Squeeze Casting

Like High and Low pressure die casting, when the vertical filling liquid front is higher than $\sim 0.5\text{m/s}$ then it becomes unstable. From experiments conducted, it was found the critical value in which air entrapment occurs was when $V_g > \sim 0.4 \text{ m/s}$ for aluminium alloys [8] so in order to prevent air entrapment, the plunger velocity must be calculated to have $V_g \cong 0.4\text{m/s}$ to avoid turbulent flow.

The design of the die will need to be optimised so there is very little to no splashback during filling. Splashback causes oxidation in aluminium alloys which affects the mechanical properties negatively. One disadvantage of squeeze casting is that it cannot be used for casting thin-wall products. This is due to reduced filling capability as the filling velocity is lower than that of HPDC. Because the V_g value is small in squeeze casting, the gate size is considerably larger compared to HPDC.

In squeeze casting there are two ways to feed. A large gate size and directional solidification. A large gate size delays solidification in that section. The die should be designed so that the gate section solidifies after the die cavity so there is always a channel into the cavity. This is so that pressure can be applied during solidification.

Directional solidification means that the liquid metal should solidify from the far end. In order to achieve this, the thicker section should be designed closer to the gate and a thinner section designed to be in the far end. Though to cast complex shapes where it is impossible to have a directional solidification, "Squeeze pins" may be used to provide localised pressure [8]

5.3 Selection of die cast process, cast alloy and post cast treatment process

If a high integrity and high strength casting is required but shape doesn't need to be highly complex, Squeeze Casting should be used. This is because squeeze casting can overcome the disadvantages HPDC has which are 1)high turbulent flow during filling and 2)insufficient feeding during solidification leading to formation of micro porosity 3)Not heat treatable so strength is around 100MPa. LPDC also cannot be used as it also has problems with micro porosity: gas pores and shrinkage pores. The gas pores are caused by the use of Hydrogen reacting with the Aluminium alloys. Although both HPDC and LPDC are widely used in manufacturing industry, they are not suitable processes to be used for structural parts that have high intensity and high strength(230MPa). For the cast alloy, aluminium would be selected because it is cheap, widely available and after heat treatment, it becomes very strong reaching over 230MPa [8]

Squeeze casting is a slower feeding process in which the hydrogen in the liquid casting is at atmospheric pressure and is then applied at 100MPa when solid. There is no hydrogen available to grow in the void of the casting.

6 Part C Questions

1) Insulating Interface:

$$t_f = \frac{\pi}{4} \left(\frac{P_s H}{T_m - T_o} \right)^2 \times \frac{1}{K_m \rho_m C_m} \times \left(\frac{v}{A} \right)^2$$

Where:

For Al

$$T_m = 660^\circ\text{C}$$

$$H = 398 \frac{\text{kJ}}{\text{kg}}$$

$$\rho = 2700 \frac{\text{kg}}{\text{m}^3}$$

For sand:

$$K_m = 0.77 \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$\rho = 2750 \frac{\text{kg}}{\text{m}^3}$$

$$C_p = 0.78 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

Max thickness = 0.065m

Solidifying from both ends = 0.0325m

$$t_f = \frac{\pi}{4} \left(\frac{2700 \times 398000}{660 - 20} \right)^2 \times \frac{1}{0.77 \times 2750 \times 0.78 \times 10^3} \times (0.0325)^2$$

$\therefore t_f = 1416.51 \text{seconds}$

2)

Gradient of composition in liquid at interface

$$-D_L \cdot \left(\frac{dC_L}{dx}\right)_{x=0} = R \cdot C_L^*(1 - k)$$

Equation for liquidus slope in phase diagram:

$$m_L = \frac{dT_L}{dC_L}$$
$$\left(\frac{dT_L}{dx}\right)_{x=0} = m_L \left(\frac{dC_L}{dx}\right)_{x=0}$$

Where the left side of the equation is the temperature gradient and the right hand side is the compositional gradient

$$G_L = \left(\frac{dT}{dx}\right)_{x=0} \geq \left(\frac{dT_L}{dx}\right)_{x=0}$$

The criterion(constitutional supercooling) for plane growth during directional solidification is given by combining the above 3 equations together.

$$\frac{G_L}{R} \geq -\frac{m_L C_S^*(1 - k)}{k D_L}$$

During steady state there is no convection in liquid $C_S^* = C_O$:

$$\frac{G_L}{R} \geq -\frac{m_L C_O(1 - k)}{k D_L}$$

$\frac{G_L}{R}$ determines solidification microstructure such as planar, cellular, columnar and equiaxed dendritic [8] also, the local cooling rate $G_L \cdot R$ is generally used to determine the scale of the microstructure [8]

Pulling speed is slow because it needs to maintain planar growth otherwise it would become cellular or even dendritic which is not single crystal, based on Czochralski process equations.

Where:

C_S^* = Solid composition at solid-liquid interface at T^*

C_L^* = Liquid composition at solid-liquid interface at T^*

3) Scheil's equation

$$C_S^* = C_o(1 - f_s)^{k-1}$$

Where:

$$\begin{aligned}k &= \frac{C_S}{C_{RL}} \\ &= \frac{12.5}{33} \\ &= 0.378\end{aligned}$$

$$f_{eut} = \left(\frac{C_{eut}}{C_o}\right)^{\frac{1}{k-1}}$$

$$f_{eut} = \left(\frac{33}{9}\right)^{\frac{1}{\left(\frac{12.5}{33}\right)-1}}$$

$$f_{eut} = 0.1235$$

$$\therefore f_{eut} = 12.35\%$$

Lever rule:

$$\begin{aligned}wt\%\beta &= \frac{AB}{AC} \\ &= \frac{33 - 12.5}{42.5 - 12.5} \\ &= 0.6833\end{aligned}$$

$$\therefore wt\%\beta = 68.3\%$$

$$\begin{aligned}F_{final\beta} &= 0.1235 \times 0.6833 \\ &= 8.43\%\end{aligned}$$

After solidification, the resulting microstructure will be dendritic Al with eutectic formation (Al) + (ω) surrounding the dendrite formations.

Low Pressure Die Casting may suffer from hydrogen porosity and shrinkage due to insufficient feeding.

4)

$$\begin{aligned}
C_s &= C_o[1 - (1 - K_e)e^{-K_e \frac{X}{L}}] \\
3 \times 10^{15} &= 7.5 \times 10^{16}[1 - (1 - 0.008)e^{-0.008 \frac{X}{2}}] \\
-0.008 \frac{X}{2} &= \ln\left(-\frac{0.4 \times 10^{15} - 10^{16}}{0.992 \times 10^{16}}\right) \\
&= \ln\left(-\frac{-9.6 \times 10^{15}}{9.92 \times 10^{15}}\right) \\
&= \ln(0.96774) \\
&= -0.0328 \\
\frac{X}{2} &= \frac{-0.0328}{-0.008} \\
\frac{X}{2} &= 4.1 \\
\therefore X &= 8.19 \text{ cm}
\end{aligned}$$

5) Given:

$$w = 0.0025 \text{ m}$$

$$I = 200 \text{ A}$$

$$V = 10 \text{ V}$$

$$\nu = 0.005 \text{ m/s}$$

$$\eta = 0.65$$

$$t = 48.5$$

0.76% Carbon Steel data:

$$k = 41 \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$\rho = 7200 \frac{\text{kg}}{\text{m}^3}$$

$$C_s = 625 \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

$$\begin{aligned}
\alpha &= \frac{41.0}{7200 \times 625} \\
&= 9.11 \times 10^{-6}
\end{aligned}$$

$$\begin{aligned}
T &= T_O + \frac{\eta \times E \times I}{2\pi \times k \times w} e^{-\frac{\nu(x-\nu t)}{2\alpha}} K_O\left(\frac{\nu\sqrt{(x-\nu t)^2 + y^2}}{2\alpha}\right) \\
T &= 293 + \frac{0.65 \times 10 \times 200}{2\pi \times 41 \times 0.0025} e^{-\frac{0.005(0.2 - 0.005 \times 48.5)}{2 \times 9.11 \times 10^{-6}}} \times K_O
\end{aligned}$$

$$\begin{aligned}
K_O &= \frac{0.005\sqrt{(0.2 - 0.005 \times 48.5 + (0.00752)^2)}}{2 \times 9.11 \times 10^{-6}} \\
&= 11.8442 \\
&= \text{BesselK}(2.710 \times 10^{-6})
\end{aligned}$$

$$\begin{aligned}
T &= 293 + 2018.55e^{11.663} \times (2.71 \times 10^{-6}) \\
\therefore T &= 928.602 \text{ K}
\end{aligned}$$

Given:

$$x = 0.2$$

$$t = 43.5$$

$$Y_{HAZ} = 7.520\text{mm}$$

$$T_O = 293\text{K}$$

$$K_O = 5.22 = 2.966 \times 10^{-3}$$

$$T = 293 + 2018.55e^{4.802} \times (2.966 \times 10^{-3})$$

$$\therefore T = 1021.94\text{K}$$

T	Δ	C_1	exp	BesselX	Bessel K_o	Temp(K)	Temp($^{\circ}$ C)
43.5		2018.55	4.802	11.5492	2.71E^{-6}	1021.94	748.94
48.5	5	2018.55	11.663	5.22	2.966E^{-3}	928.607	655.60
55	11.5	2018.55	20.58	20.68	3.105E^{-10}	873.22	600.2
60	16.5	2018.55	27.44	27.52	2.450E^{-13}	715.597	452.59
65	21.5	2018.55	34.302	34.36	2.446E^{-16}	685.909	412.90

Table 2: Table of values for X

T	Δ	C_1	exp	BesselX	Bessel K_o	Temp(K)	Temp($^{\circ}$ C)
43.5		2018.55	4.802	4.87	4.597E^{-3}	1502.28	1229.28
48.5		2018.55	11.663	11.7	2.710E^{-6}	928.6	655.602
55	6.5	2018.55	20.58	20.6	3.105E^{-10}	836.1	563.102
60		2018.55	27.44	27.45	3.003E^{-13}	793.76	520.76
65		2018.55	34.302	34.302	2.446E^{-16}	682.641	409.64

Table 3: Table of values when $y_{fusion} = 0.003035$

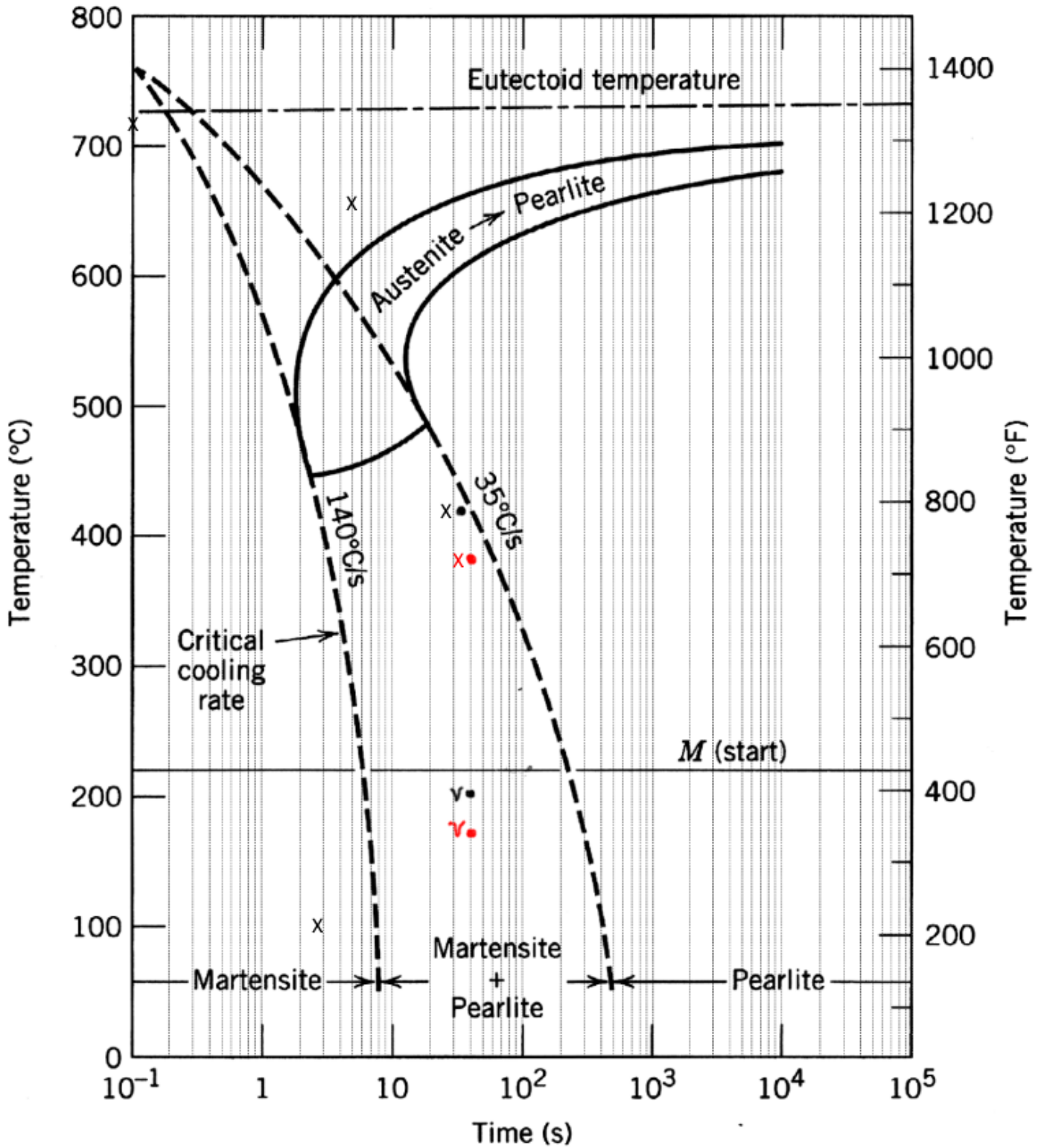


Figure 17: Plot of temperature data [8]

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