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Study of the Industrial Precision Manufacturing and Metallic Alloys with Respect to Economic Considerations

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Abstract
In this report according to the research results and approaches that used, it is utilized and illustrated why these papers are suitable for this research. The best position for explaining topic is here, because for understanding better the concept and the area of research, it is necessary to write briefly at the beginning of the article about topic. It is attempted to design new piston (porous piston) not only to have a good resistance in mechanical properties but also provide lower weight comparing to the previous ones. The most important thing in this work is to be aware of the effect of vibration, vacuum and over pressure during investment casting which by this way we can produce porous structure. By using the existing results of several papers, we will attempt to cast porous piston and optimize it to have the best mechanical properties. As we know engine pistons are one of the most complex components among all automotive or other industry field components. The engine can be called the heart of the car and piston maybe considered the most important part of an engine.

Keywords: Porous piston, mechanical properties, investment casting

Introduction
Aluminum alloys are one of the most popular materials for structural component in engineering industry such as automotive, aerospace and construction environmental. The most important factors of aluminium that make it the best are low specific weight and low melting point. By this way, aluminium has a good corrosion resistance, high strength and stiffness to weight ratio, excellent formability, weldability, high electrical and heat conductivity. Firstly, we must to know the needs of the design community, its means understanding the needs of designers. Secondly, for industrial casting should have the equipment to tailor and optimize alloys for specific applications [1]. For commercial applications, a wide range of casting aluminum alloys is used. For instance, in power networks, the aluminum casting can help to reduce harmonics in transmission level resulting in lower marginal prices for the end customers [2] as well as reducing the implementation cost of the storage systems to increase the system's return rate [3]. It can also can affect the islanding detection in microgrids by affecting the islanding detection apparatus installed in the system [4]. Also, they are employed as high strength aluminium alloy casings in new breed of yokeless axial electric machines. [5, 6] The other important usages are for those based on the Al–Si, Al–Si–Mg and Al–Si–Cu systems. Generally, in order to classify alloys, if prepared from new metals are called "primary" otherwise if they produce from recycled materials are named "secondary". Generally more undesirable impurity elements are in the secondary alloys that complicate their metallurgy and often lead to properties lower than those of the equivalent primary alloys. The specific benefits of aluminium alloys for castings apart from light weight are the comparatively low melting temperatures, negligible solubility

for all gases except hydrogen, and the excellent surface finish that is commonly obtained with final products. Compositions selected with solidification ranges suitable to special applications because most alloys display good fluidity. High shrinkage that takes place in majority aluminium alloys during solidification is one of the major problems with aluminium castings [7].

By unique number series most alloying elements and particular combinations of elements are exhibited as follows in the ANSI (NADCA) numbering system in table 1:

Table 1 ANSI numbering system [2]

Number Series	Alloy Type
1XX.X	99.0% minimum aluminum content
2XX.X	Al + Cu
3XX.X	Al + Si & Mg, or Al + Si & Cu, or Al + Si & Mg & Cu
4XX.X	Al + Si
5XX.X	Al + Mg
7XX.X	Al + Zn
8XX.X	Al + Sn

The production form indicates with the decimal in each alloy number. A zero (0) in the decimal exhibits the casting production (die casting, for instance). A one (1) in the decimal reveals the chemistry limits for ingot utilized to make the XXX.0 product. A two (2) in the decimal also shows ingot utilized to make that XXX.0 product, but ingot of slightly different (usually tighter) chemistry limits than that of XXX.1. For example, a nomination 380.0 could exhibit a die casting production seemingly produced from 380.1 secondary ingots whereas 356.0 might reveal a squeeze casting production produced from 356.2 primary ingots. The significant things are to remember that a "0" in the decimal exhibits a cast product inasmuch as a "1" or "2" reveals the ingot chemistry required to make the cast product. The "XXX.1" or "XXX.2" ingot specifications are always slightly tighter than the "XXX.0" specifications for the cast part. And in accord with agreement, "XXX.2" ingot always has tighter chemistry limits than "XXX.1" ingot in table 2:

Table 2 example of xxx.0, xxx.1 and xxx.2 [2]

Alloy	Form	Si	Fe	Cu	Mn	Mg	Zn	Ti	Each	Total
360.0	die casting	9.0 - 10.0	2.0 max	0.6 max	0.35 max	0.40 - 0.6	0.50 max	-	-	0.25 max
360.2	ingot	9.0 - 10.0	0.7 - 1.1	0.10 max	0.10 max	0.45 - 0.6	0.50 max	-	-	0.25 max
A360.0	die casting	9.0 - 10.0	1.3 max	0.6 max	0.35 max	0.40 - 0.6	0.50 max	-	-	0.25 max
A360.1	ingot	9.0 - 10.0	1.0 max	0.6 max	0.35 max	0.45 - 0.6	0.40 max	-	-	0.25 max
A360.2	ingot	9.0 - 10.0	0.6 max	0.10 max	0.05 max	0.45 - 0.6	0.05 max	-	0.05 max	0.15 max

A "XXX.1" secondary-alloy ingot will be had by most of the traditional die casting alloys and a "XXX.2" primary ingot will be had by "premium castings" alloys [1].

Generally, alloy regularly and believably produces castings that have perfect microstructures and are dimensionally accurate for most of products, processes and plants, it can be described as being castable. Fluidity, mould-filling ability, volume shrinkage, susceptibility to hot tearing, porosity-forming characteristics and surface quality are the most remarkable factors for castability of an alloy. In below these factors are debated. Particularly chemical composition effect on some factors although mould design and process conditions are usually more significant [7].

The Aluminum Association's Designations and Chemical Composition exhibits for Aluminum Alloys as Castings and Ingot describes for each alloy 10 special alloying elements and also has a column for "others". In addition, in some elements such as Sr, microstructural control and mechanical properties are very significant while in the Aluminum Association document they are not particularly recognized and are just comprised in the category "others". For purposes of comprehending their effects and notability, for the majority of alloys that classify as major, minor, microstructure modifiers or impurities; understanding for alloying elements, however, that impurity elements in some alloys might be major elements in others [1]:

- Major elements specially comprise silicon (Si), copper (Cu) and magnesium (Mg)
- Minor elements comprise nickel (Ni) and tin (Sn) witch found greatly in alloys that probably would not be utilized in high unity die castings
- Microstructure modifying elements contain titanium (Ti), boron (B), strontium (Sr), phosphorus (P), beryllium (Be), manganese (Mn) and chromium (Cr)
- Impurity elements specially comprise iron (Fe), chromium (Cr) and zinc (Zn).

1.2 Major Elements

1.2.1 Al–Si alloys

Recently, Al–Si alloys are the most usual materials in the casting aluminum alloys. These alloys present many benefits such as wear and corrosion resistance, hot tearing resistance, good weldability, high strength to weight ratio and excellent castability, hence, these alloys are suitable for automotive cylinder heads, engine blocks, and aircraft components, pipe fitting and military applications [8]. Binary Al–Si alloys until the eutectic composition preserve excellent levels of ductility, preparing the iron content is controlled to minimize formation of large, brittle plates of the compound β–AlFeSi. In this regard, additions of manganese have been understood to be profitable because this element prefers arrangement of the finer α–AlFeSi phase which has known as Chinese script morphology. Role that accepted in industry is that the Mn:Fe ratio requires to be at least 0.5:1 for β–AlFeSi to be suppressed, despite the fact that the latter phase has been seen in alloys with Mn:Fe ratios as high as 1:1. However, such high levels of manganese can be a disadvantage since they may

promote formation of greater volume fractions of intermetallic compounds than are presented for the same levels of iron [7].
One of the most important alloying components in the majority of aluminum casting alloys is Silicon (Si). Known as "good castability" is mainly affected by Silicon; i.e., the ability to willingly fill dies and to solidify castings with no hot tearing or hot cracking issues:
The α-aluminum solid solution is the matrix of casting aluminum-silicon. It crystallizes in the form of nonfaceted dendrites, on the basis of crystallographic lattice of aluminum. This is a face centered cubic (FCC) lattice system, noted by the symbol *A*1, with coordination number of 12, and with four atoms in one elementary cell (Ref 1–3). Lattice *A*1 is one of the closest packed structures, with a very high filling factor of 0.74 (see Figure 1).

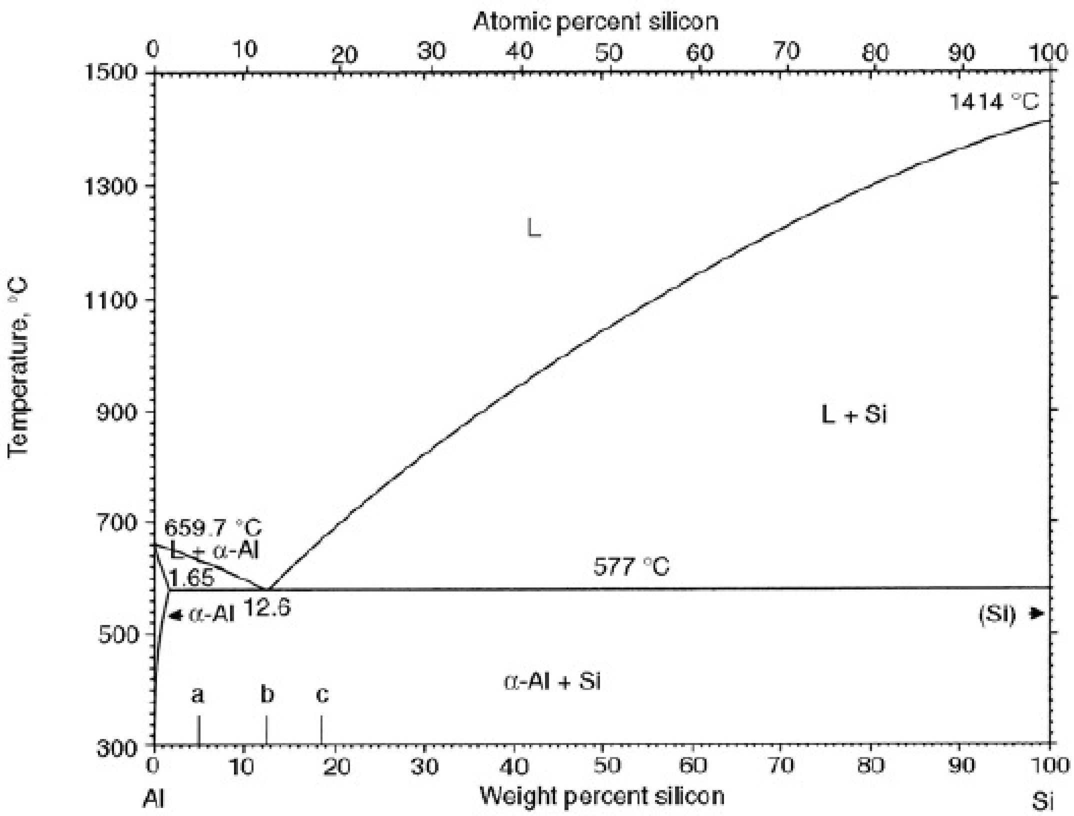

Figure 1 Commercial cast aluminum-silicon alloys equilibrium diagram

- Silicon's high heat of fusion is one of the advantages of casting based on Al-Si system that increase the alloy's "fluidity" or "fluid life" (the distance the molten alloy can flow in mould before being too cold to flow further).
- Maximum solid solubility that has been limited by silicon is 1.65wt%. In any event alloys with more than a few percent silicon endure a comparatively large volume fraction of isothermal solidification have been mean by eutectics with aluminum at a obviously high level 12%, therefore they acquire significant strength while undergoing little or no thermal contraction, very significant to avoiding hot tearing or hot cracking issues.

- The lower thermal expansion coefficient is in an alloy contains more silicon. The silicon phase in Al-Si system reduces both shrinkages during solidification and coefficient of the thermal expansion of the cast products.
- Silicon causes significantly to alloys wear resistance because it is a very hard phase.
- For improving an alloy's strength and to making alloys heat treatable, silicon reacts with other elements.
- If before being into exalted temperature service the part is not thermally stabilized, Silicon can cause a permanent increase in a casting's dimensions.

At a single temperature pure aluminum (Al) solidifies isothermally. Within a very narrow temperature window Eutectic compositions, Al with 12% Si for example 413 alloy also, solidify fundamentally isothermally. From the die surface toward the thermal center of the casting's cross-section they tend to solidify progressively. Between the remaining liquid and the solidified portion exists a very narrow plane of demarcation. That minimum leaning to hot tear during casting is supplied by solidification sample. A sound skin extending toward the thermal center of the casting section is produced by the planar front solidification of very narrow freezing range alloys. At the end of solidification, any liquid to solid transition shrinkage is confined along the thermal centerline of the casting. Because solidification shrinkage is not connected to the surface of the casting, castings produced from such alloys are usually pressure tight. For strength of aluminum casting alloys, Silicon lonely affected but not importantly. In any event, Si supplies a very impressive strengthening mechanism in aluminum castings when joined with magnesium. Approximately 0.7% Mg is soluble in the solid alloy and supplies the precipitation strengthening basis for whole family of heat-treatable alloys (alloy numbers 356 through 360 and their many variations). Thermal expansion coefficient and specific gravity will be decreased by increasing the silicon level in an alloy. In addition Silicon also increases an alloy's wear resistance, which has often made aluminum silicon alloy castings attractive substitutes for gray iron in automotive applications. In many of pumps, compressors, pistons and automatic transmission components widely in premium aluminum bare-bore engine blocks use the hypereutectic Al-Si alloys such as B390 [1].

1.2.2 Al-Si-Mg alloys

The small additions of magnesium supply significant age hardening through precipitation so large amount of sand and permanent mould castings are made from the Al–Si–Mg. For example, the yield strengths of Al-Si-Mg alloys in the T6 condition are more than double of Al-Si alloy with the same amount of silicon and these alloys for secondary precipitation have good reaction. Furthermore they reveal that having extraordinary corrosion resistance. Both alloys are used for critical castings in aircraft and automotive components such as accurate cast wing flap tracks for models of the European Airbus series, cylinder heads and wheels [7].

Magnesium use to strengthen and harden aluminum castings. Silicon joins with magnesium for hardening phase as exhibited previously in this section for example Mg2Si that supplies the strengthening and heat treatment basis for the famous 356 family of alloys. In addition, Magnesium is a strengthening element in the high magnesium 5XX alloys that include very small amount of silicon but acquire moreover from other magnesium bearing phase. Heat-treating ordinarily doesn't improve the binary Al-Mg' strength, however, these alloys have extraordinary strength and ductility in the as-cast and room temperature self-aged condition. Binary Al-Mg alloys have marginal castability but have low fluidity because of lack of silicon they desire to be hot-short, However, they have perfect corrosion resistance, machinability and they desire to anodized to a natural aluminum color [1].

1.2.3 Al–Si–Cu alloys

For enhancing age hardening and strength casting of Al–Si alloys are used copper. In addition copper enhances machinability but castability, ductility and corrosion resistance are all decreased. For pressure diecastings use the higher silicon alloys for example Al–10Si–2Cu, despite for sand and permanent mould castings use alloys with lower silicon and higher copper for example Al–3Si–4Cu. Artificial ageing (T5 temper) in many cases enhance the strength and machinability of some of these castings. Generally for where that needs higher strength the Al–Si–Cu alloys are used for many of the requests that listed for the binary alloys for example alloy 319 (Al–6Si–3.5Cu) use for permanent mould die cast automotive engine blocks and cylinder heads in place of cast iron. Machining characteristics are enhanced by some compositions that include few additions of elements such as bismuth as with the wrought alloys. One example of more various compositions that are attainable for where which exceptional properties are required is the piston alloys for internal combustion engines such as A332(Al–12Si–1Cu–1Mg–2Ni) whereas, nickel improves exalted temperature properties [7]. Copper (Cu) improve the strength and hardness of aluminum casting alloys. In addition by increasing matrix hardness copper enhances the machinability of alloys because it is easier to produce small cutting chips and fine machined finishes. On the downside, copper generally reduces the corrosion resistance of aluminum; and, in certain alloys and tempers, it increases stress corrosion susceptibility. Also Aluminum-copper alloys have comparatively poor fluidity and resistance to hot tearing during solidification which do not contain at the lowest temperate amounts of silicon. In spite of the fact that alloys with up to 10% copper were popular in the aluminum foundry industry before but today they have been replaced by silicon including alloys [1].

1.3 Minor Elements

1.3.1 Nickel and Tin

The elevated temperature service strength and hardness of 2XX alloys are improved by Nickel (Ni). For the same aim in some 3XX alloys Nickel is utilized but effectiveness of Nickel in the silicon concluding alloys is less surprising [1].

For the purpose of reducing friction in bearing and bushing applications in 8XX aluminum casting alloys are used Tin (Sn) that melts at a very low temperature (227.7 C). Under emergency conditions if such bearings/bushings seriously overheat in service Tin can supply short term liquid lubrication to rubbing surfaces. Usually for die casting the 8XX series alloys are not suitable or its variations [1].

1.4 Impurity Elements

1.4.1 Iron

In most traditional die casting alloys Iron (Fe) is exhibited as a very useful impurity. In concentrations of 0.8% or more Iron extremely decreases the tendency of an alloy to solder to die casting tooling. At about 0.8% Fe, the Al-Fe-Si composition takes place. Theoretically, the molten alloy and die are in close contact while the supersaturated molten alloy has few tendency to dissolve the comparatively unprotected tool steel, when iron is alloyed to a bit more than 0.8%. Aluminum, silicon, and other elements join with Iron to create a different of hard, complex insoluble phases. Morphologies supply stress risers that significantly decrease the ductility of an alloy. Iron concentration and the solidification conditions (rate) are functions for their volume fraction and size. Die casting is able to endure higher iron levels than other casting processes for platelets because they desire to be fewer and smaller at higher solidification rates. Iron in high integrity die casting variations such as high-vacuum, squeeze and semi-solid casting cannot be endured at high concentrations. A major purpose for those cases is to have high ductility by supplying numerous stress risers and points of crack initiation. Primary alloys in those cases are more traditionally used in sand and permanent mold casting also they have become the popular options for high integrity die casting. At concentrations more than 0.4% Manganese has been exhibited to supply sufficient protection versus soldering, so alloys designed for high integrity vacuum die casting [1].

2. Alloy selection

The best material that we desire, requires to have good fluidity [9] for having complete microstructure without misrune and have a good mechanical properties, so according to the of tables 3, the best material is A413.0 with mechanical composition which is exhibited in table 4.

Table 3 Mechanical properties and foundry characteristics of selected casting alloys [7].

Aluminium Association number	BS 1490 LM number	Casting process	Temper	0.2% proof stress (MPa)	Tensile strength (MPa)	Elongation (% in 50 mm)	Casting characteristics: Fluidity	Pressure tightness	Resistance to hot tearing	Corrosion resistance	Weldability	Machining
201.0		S†	T6	345	415	5.0	C	D	D	D	C	B
208.0		S	T533	105	185	1.5	B	B	B	D	B	C
213.0		PM	T533	185	220	0.5	B	C	C	E	C	B
	LM4	S and	T21	95	175	3.0	B	B	B	C	C	B
		PM	T6	230	295	2.0						
242.0	LM14	PM	T6	230	295	1.0	C	C	D	D	D	B
295.0		PM	T61	195	260	4.0	C	D	D	D	C	B
319.0	LM21	S	T21	125	185	1.0	B	B	B	C	B	C
		PM	T21	125	200	2.0						
		S and PM	T61	240	260	0.5						
332.0	LM13	PM	T65	295	325	0.5	B	C	A	C	B	B
355.0	LM16	S	T4	125	210	3.0	B	B	B	C	B	B
		PM	T4	140	245	6.0						
		PM	T6	235	280	1.0						
356.0	LM25	S	T6	205	230	4.0	B	A	A	B	B	C
		PM	T6	225	240	6.0						
357.0		S	T6	275	345	3.0	B	A	A	B	B	C
		PM	T6	295	360	6.0						
360.0	LM9	S	T5	110	185	2.0	A	B	A	B	B	C
		S	T6	215	255	–						
		PM	T5	130	245	2.5						
		PM	T6	265	310	1.0						
	LM6	S	F1	65	185	8.0	A	B	A	A	B	C
		PM	F1	90	205	9.0						
		D	F1	130	250	2.5						
413.0	LM20	D	F1	140	265	2.0	A	A	A	B	A	C
443.0	LM18	S	F1	65	130	5.0	B	A	A	A	B	C
		PM	F1	70	160	6.0						
514.0	LM5	S	F1	80	170	5.0	C	D	C	A	C	B
		PM	F1	80	230	10.0						
518.0		D	F1	130	260	10.0	D	E	C	A	A	A
520.0	LM10	S	T1	175	320	15.0	D	E	B	A	E	B
535.0		S	F	145	275	13.0	D	E	C	A	A	A
705.0		S	T1	130	240	9.0	D	C	E	B	D	A
707.0		S	T1	185	255	3.0	D	C	E	B	D	A
713.0		S	T5	175	235	4.0	D	C	E	B	D	A

Notes: S = sand casting; PM permanent mould (gravity die) casting; D = pressure diecasting

†Results for sand cast alloys obtained from separately cast test bars

Tensile properties for all alloys generally represent "best practice" in casting procedures

Ratings for casting characteristics A through to E in decreasing order of merit

Table 4 Compositions of selected aluminium casting alloys [7].

Association number	BS 1490 LM number	Casting process	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other
150.1	LM 1	Ingot	†	†	0.10					0.05		99.5 Al min
201.0		S	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55				0.15–0.35	Ag 0.40–1.0
208.0		S	2.5–3.5	1.2	3.5–4.5	0.50	0.10		0.35	1.0	0.25	
213.0		PM	1.0–3.0	1.2	6.0–8.0	0.6	0.10		0.35	2.5	0.25	
	LM 4	S and PM	4.0–6.0	0.8	2.0–4.0	0.20–0.6	0.15		0.30	0.50	0.20	
238.0		PM	3.5–4.5	1.5	9.0–11.0	0.6	0.15–3.5		1.0	1.5	0.25	
242.0	LM 14	S and PM	0.7	1.0	3.5–4.5	0.35	0.15–0.35	0.25	1.7–2.3	0.35	0.35	
295.0		S	0.7–1.5	1.0	4.0–5.0	0.35	0.03			0.35	0.25	
308.0		PM	5.0–6.0	1.0	4.0–5.0	0.50	0.10			1.0	0.25	
319.0	LM 21	S and PM	5.5–6.5	1.0	3.0–4.0	0.50	0.10		0.35	1.0	0.25	
328.0		S	7.5–8.5	1.0	1.0–2.0	0.20–0.6	0.20–0.6	0.35	0.25	1.5	0.25	
A332.0	LM 13	PM	11.0–13.0	1.2	0.50–1.5	0.35	0.7–1.3		2.0–3.0	0.35	0.25	
355.0	LM 16	S and PM	4.5–5.5	0.6‡	1.0–1.5	0.50‡	0.40–0.6	0.25		0.35	0.25	
356.0	LM 29	S and PM	6.5–7.5	0.6	0.25	0.35	0.20–0.40			0.35	0.25	
A356.0	LM 25	S and PM	6.5–7.5	0.20	0.20	0.10	0.20–0.40			0.10	0.20	
357.0		S and PM	6.5–7.5	0.15	0.05	0.03	0.45–0.60			0.05	0.20	Be 0.04–0.07
360.0	LM 9	D	9.0–10.0	2.0	0.6	0.35	0.40–0.6		0.50	0.50		
380.0	LM 24	D	7.5–9.5	2.0	3.0–4.0		0.50	0.10	0.50	3.0		
A380.0	LM 24	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10		0.50	3.0		
390.0	LM 30	D	16.0–18.0	1.3	4.0–5.0	0.10	0.45–0.65			0.10		
	LM 6	S, PM and D	10.0–13.0	0.6	0.10	0.50	0.10		0.10	0.10	0.20	
413.0	LM 20	D	11.0–13.0	2.0	1.0	0.35	0.10		0.50	0.50		
	LM 2	D	9.0–11.5	1.0	0.7–2.5	0.50	0.30		0.50	2.0	0.20	
443.0	LM 18	S	4.5–6.5	0.8	0.6	0.50	0.05	0.25		0.50	0.25	
514.0	LM 5	S	0.35	0.50	0.15	0.35	3.5–4.5			0.15	0.25	
518.0		D	0.35	1.8	0.25	0.35	7.5–8.5		0.15	0.15		
520.0	LM 10	S	0.25	0.30	0.25	0.15	9.5–10.6			0.15	0.25	
535.0		S	0.15	0.15	0.05	0.1–0.25	6.2–7.5				0.10–0.35	
705.0		S and PM	0.20	0.8	0.20	0.40–0.6	1.4–1.8	0.2–0.4		2.7–3.3	0.25	
707.0		S and PM	0.20	0.6	0.20	0.40–0.6	1.4–1.8	0.2–0.4		4.0–4.5	0.25	
712.0		PM	0.15	0.50	0.25	0.10	0.50–0.65	0.4–0.6		5.0–6.5	0.10–0.25	
713.0		S and PM	0.25	1.18	0.40–1.0	0.6	0.20–0.50	0.35	0.15	7.0–8.0	0.25	
850.0		S and P	0.7	0.7	0.7–1.3	0.10	0.10		0.7–1.3		0.20	Sn 5.5–7.0

Notes: Compositions are in % maximum by weight unless shown as a range
S = sand casting; PM = permanent mould (gravity die) casting; D = pressure diecasting

†Ratio Fe: Si minimum of 2:1

‡If iron exceeds 0.45% manganese content must be less than one-half the iron content

3 Metal Castings

Metal castings form [10] of devices schematically is shown below:

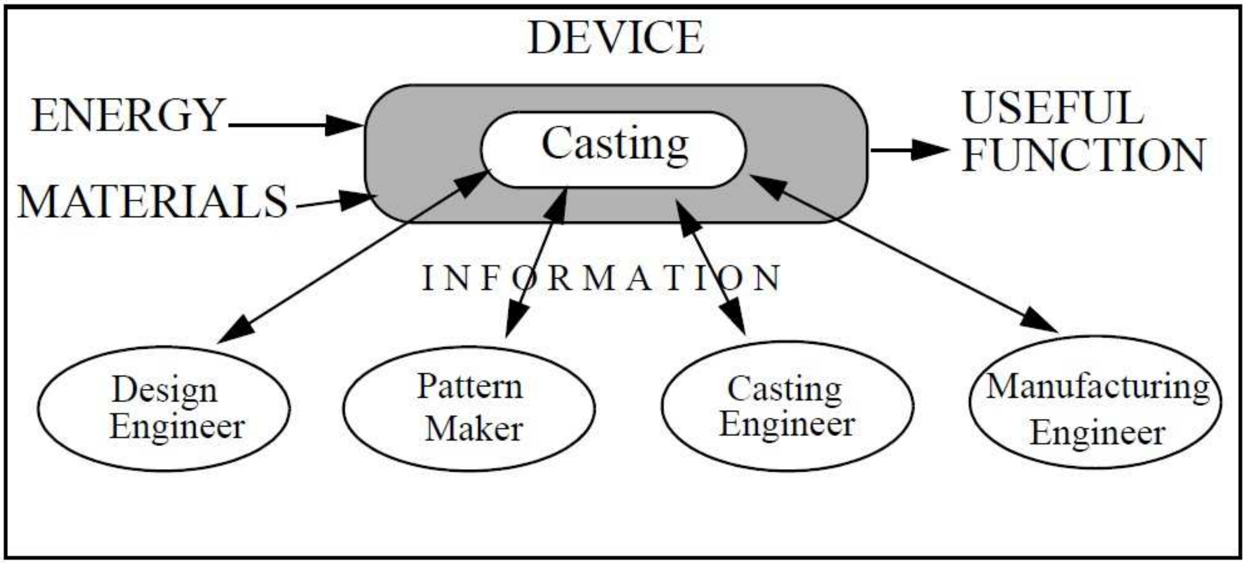

Figure 8 Metal casting Devices [10]

Engineering determine each cast component which has a shape, size, chemical composition and metallurgical microstructure at by:
A. Design Engineers is done with Mechanical Engineers
B. Pattern Makers is done with skilled craftsman and CAD
C. Casting Engineers is done with Metallurgical Engineers
D. Manufacturing Engineers is done with Mechanical and Metallurgical Engineers

For possessing a timely and cost effective manner during casting performance, engineering professionals share information during performance the process and work together.

3.1 Metal Casting Process

The metal casting [35] process is the simplest and often at least cost. For pour into the mold a mold cavity of the desired shape and molten metal cavity is required for this process. Most often pouring molten metal into molds made of sand have been produced by human's beings for thousands of years. A basic component of a mold cavity contains cope, drag, parting line, riser, sprue, pouring basin, part of the molten metal handling system is known as a ladle, etc. is shown below [10]:

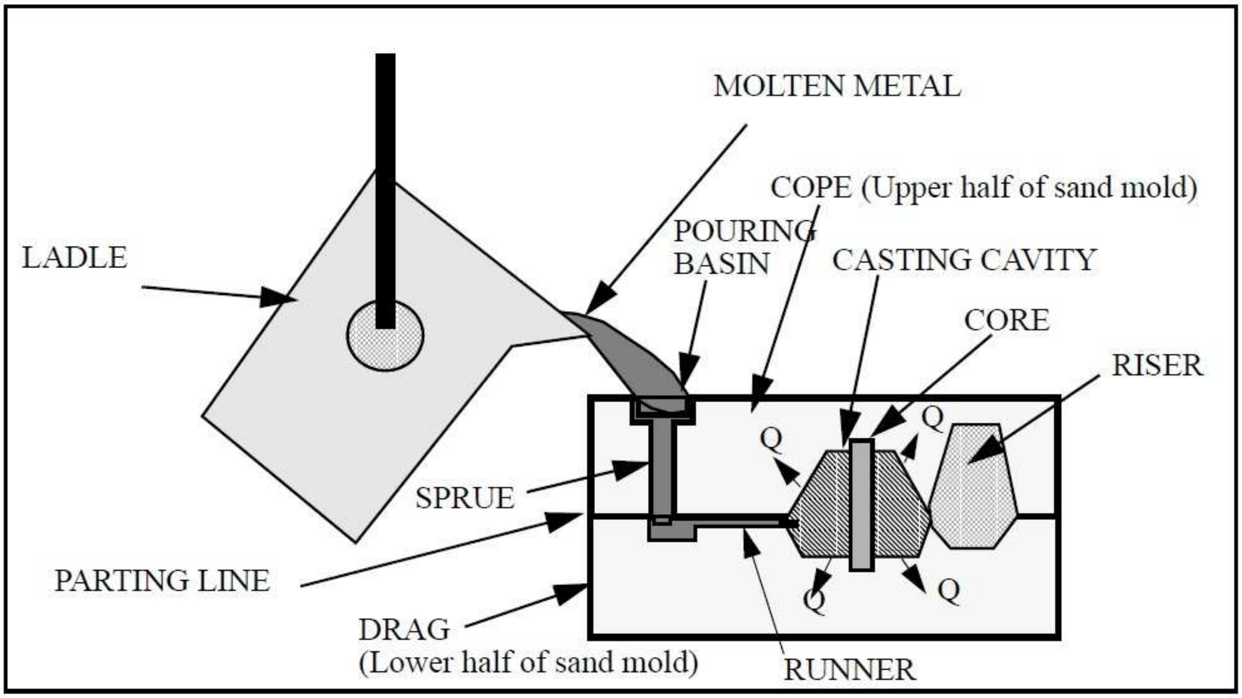

Figure 9 a basic component contains a mold cavity [10].

Making castings has traditionally been an art form by the production of molten metal and molds. Metal casting has been used for producing practical instruments for human usage in addition to beautiful works of art. For producing suitable castings the ancient artisan used traditions and learned skills that learned through the ages and used that experience. Therefore modern producer of industrial castings use these same skills but expand that skills with an understanding of the fundamental principles of fluid flow, heat transfer, thermodynamics and metallurgical microstructural development.

3.2 Metal Casting Design

A methodical combine of experience and engineering basic are the precepts of prosperous casting to commencement the casting [10]. In six steps (that show in Figure 7) most important components of the design process are exhibited.

1 Physical Design of Part to be Cast such as Size and Shape, Tolerances with manufacturing and engineering, change of Dimensional in processes, Relationship of this Part to Others to Optimize its Design by Concurrent Engineering
2 Select the Material of Part for casting.
3 For Molds and Cores Gating and Riser Design by applying pattern production, Fluid flow and Heat Transfer
4 Select the Casting Process, Limit the Casting Production because of metal cast, casting size, dimensional requirements for Produce
5 Process of Machining, heat treating and welding for After Casting
6 Evaluate the Casting Production

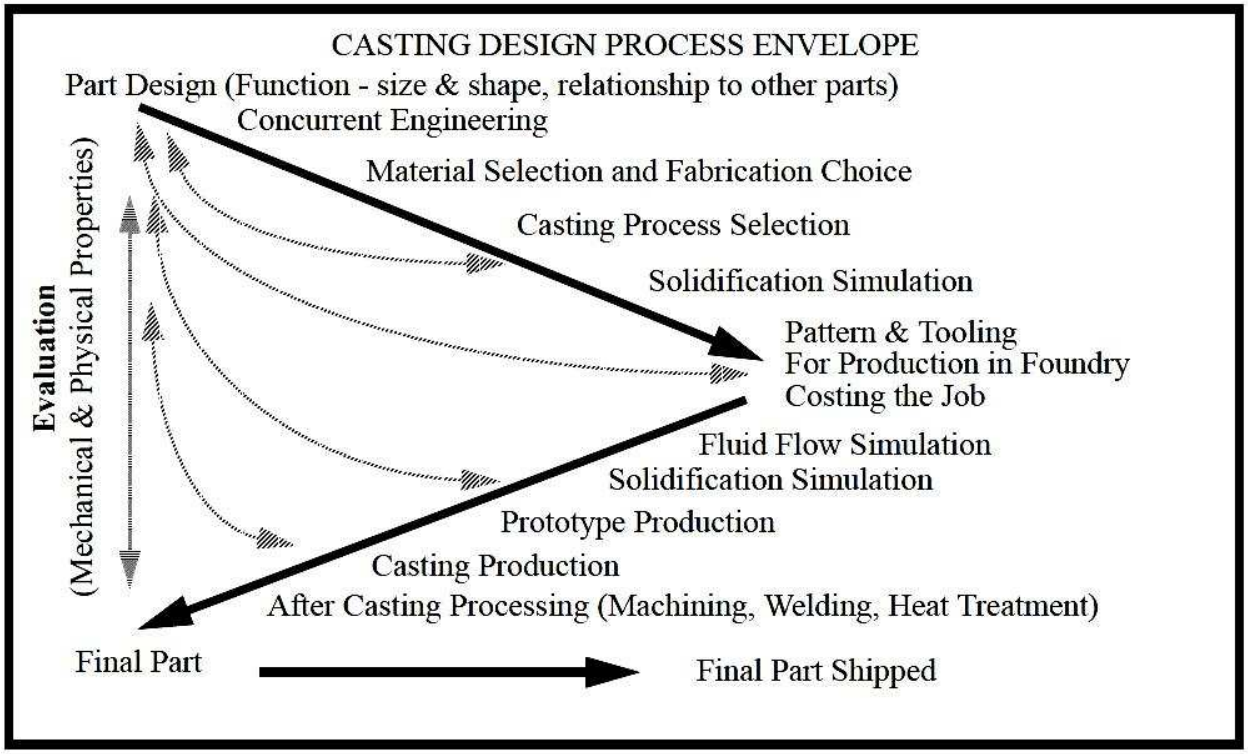

Figure 10 the design process [10]

Pattern is an integral part of the casting process which making it is a time-honored skill. Patterns are ordinarily produced from wood, plastics. Metallic pattern depend on the intricacy of the casting being produced, the number of castings required and clearly on the capability of the pattern shop that is involved.

4 Different way of casting

4.1 Rapid Prototyping

Rapid prototyping is a technology that 3-D models as an example patterns or molds can be built by producing additive layer-by-layer CAT scan type slices of a pattern in plastics, waxes, or paper, or of CAT scan type slices of a mold in ceramics [11-13].

4.1.1 Stereolithography

Three dimensional **plastic** objects are produced directly from CAD data in Stereolithography process [11].

4.1.2 Laminated Object Manufacturing

Laser cutting of heat sensitive paper produce three dimensional **paper** parts are produced by in laminated object manufacturing process [11].

4.1.3 Selective Laser Sintering

Three dimensional **plastic** objects are created directly from a CAD file in Selective laser sintering process [11].

4.1.4 Fused Deposition Modeling

Depositing thermoplastic material produce three dimensional **thermoplastic** objects in thin layers at fused deposition modeling process [11].

4.1.5 Solid Ground Curing

Photo-polymer resins are used to build up a 3D part in Solid ground curing process [11].

4.1.6 Direct Shell Production Casting

A layering process produces a **ceramic mold** in DSPC process [11].

4.2 Sand Casting Processes

The tolerances on sand casting processes are generally wider than the other casting methods. The material costs for the process are low and the sand casting process is unusually flexible. The sand used for green sand molding is critical and determines the favorable or unfavorable outcome of the casting. It controls the tolerances, surface finish and the repeatability while in production [11].

4.3 Lost Foam or Evaporative Pattern Casting

For producing complex, close-tolerance castings, the lost foam process is an economical method and in recent years casting designers growing in popularity. By preparing a pattern of polystyrene made Lost foam castings [11].

4.4 DIE CASTING

Molten metal commonly a low melting point material such as Al, Zn or Mg alloys is injected under pressure into a permanent mold in Die casting process. Die casting is a very commonly used type of permanent mold casting process. It is used for producing many components of home appliances such as rice cookers, stoves, fans, washing and drying machines, fridges, motors etc. Die casting molds are expensive and required significant lead time to fabricate. There are two common types of die casting: hot- and cold-chamber die casting [11].

4.5 Squeeze Casting

A hybrid machine casting process which joins features of forging and casting in one performance is Squeeze casting [11].

4.6 Shell-mold casting

For possessing better surface quality and tolerances is used shell mold casting which 2 pieces pattern is made of metal for example aluminium or steel, heated between 175°C-370°C and coated with a lubricant such as silicone spray [11].

4.7 Plaster-mold casting

By mixing plaster of pairs CaSO4 make the mold of Plaster-mold casting. This is a fine white powder which mixed with water become a clay-like consistency and can be shaped around the pattern (it is the same material that used to make casts for people if they fracture a bone) [11].

4.8 Ceramic mold casting

This process is similar to plaster-mold casting except that ceramic material is used for mold for example silica or powdered Zircon $ZrSiO_4$ and also Ceramics are refractory and have higher strength that plaster [11].

4.9 Vacuum casting

Also this process is introduced as counter-gravity casting. It is fundamentally the same process as investment casting, except by a vacuum pump sucks the material into the mould for the step of filling the mold [11].

4.10 Permanent mold casting

In the Permanent mold casting two halves of the mold is made of metal that usually used cast iron, steel, or refractory alloys for molds. The cavity includes the runners and gating system is machined into the mold halves. For hollow parts, either permanent or sand-bonded ones may be used. It is depend on whether the core can be extracted from the part without damage after casting. The surface is covered with a spray of graphite or silica before molding [11].

4.11 Investment Casting (Lost Wax Process)

In investment casting design is prepared usually out of wax and putted inside a metal cylinder which called a flask. Nearby the wax shape, wet plaster is poured into the cylinder. The cylinder includes the wax pattern and plaster is putted in a furnace, after the hardening of plaster, and is heated till the wax has completely vaporized. The flask is took off from the furnace after the wax has fully burnt-out, and by the wax molten metal pours into the cavity left. After cooling of the metal plaster is chipped away and the metal casting is exhibited. One of the suitable processes for producing sculptural objects or engineering shapes with complicated geometry (such as transmission housings) in metal Investment casting process. By this process some models which would be difficult to machine are more comfortable to cast. One of the important advantages of the investment casting process rather than sand casting process is that by this way it is easy to undercut in the pattern. Pattern in sand casting needs to be taken out after it is packed, whereas by heating the pattern in the investment casting will be vaporized. In addition investment casting process is very readily for producing Hollow, thinner sections, and also better surface finish will be generally achieved. But investment casting rather than sand casting is more costly and takes a long time for doing process [14].

4.11.1 Step by step process

By using the Stanford's facilities in the investment casting process, there are a few different variations. One of the most common procedures is here.

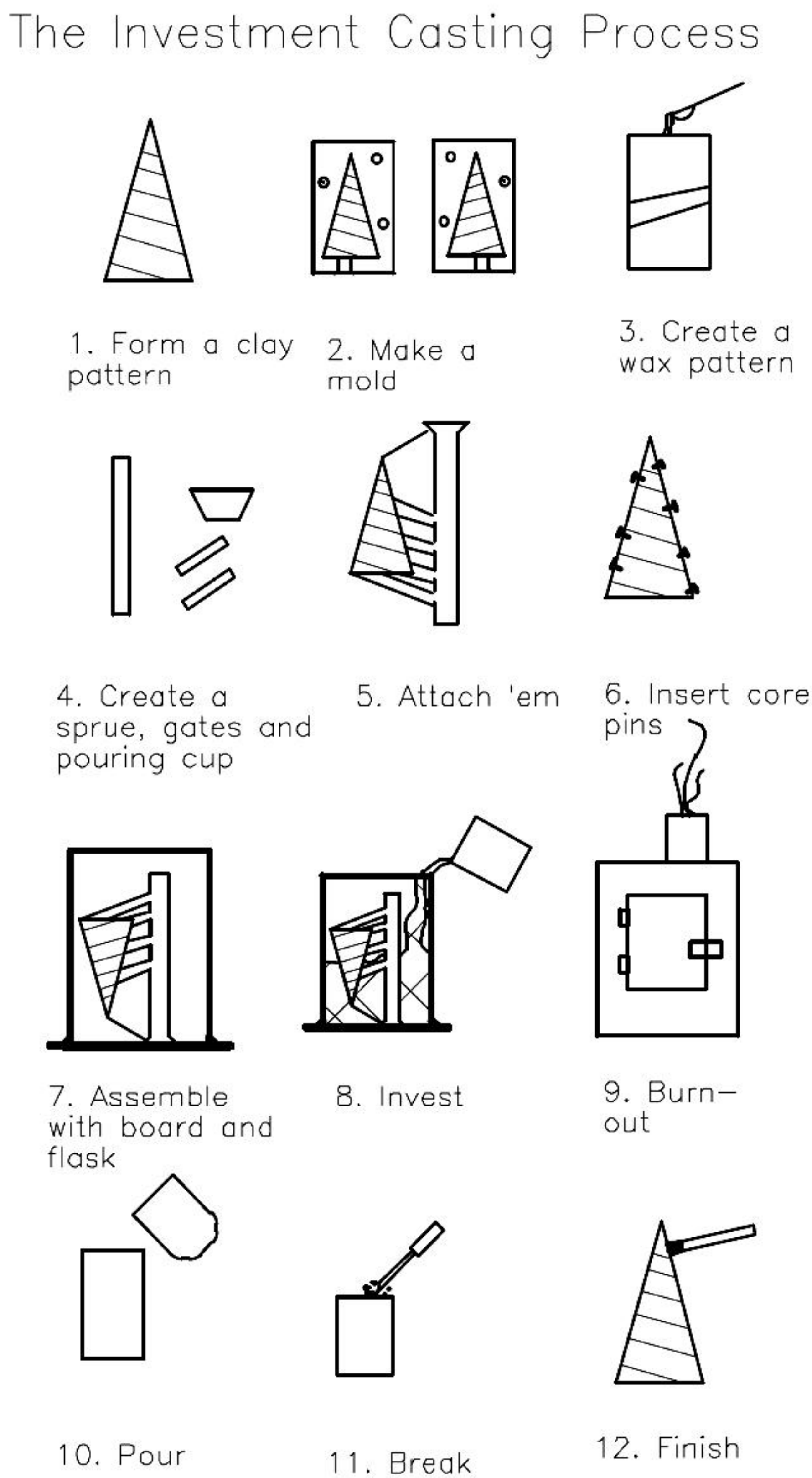

Figure 11 investment casting process [10]

4.11.1.1 Form a master pattern

Anything that holds shape at least logically perfect is able to make the pattern. Sculpey or modeling clay is both the best choices because they hold their shape excellent and for forming are comfortable [14].

4.11.1.2 Make a mould

The negative shape of the pattern is mold. A blend including of casting plaster, sand, and water produce the mold. 30-30 mix is the dry mixture of 1 part 30-minute casting plaster and 2 parts 30-grit sand, which forms viscous slurry when mixed with water [14].

4.11.1.3 Create a hollow wax pattern

For founder to get wax pattern from reproduction mould, there are a number of methods that can use. The exact methods that used are variable according to the individual preferences of each foundry workshop and the particular challenges of the job in hand. One of the most common methods is known as slushing [14].

4.11.1.4 Create sprue, gates and a pouring cup

Possessing well sprue and gate design is necessary. The bottom gating should be used for gravity-poured castings (at the PRL, most anything larger than about the size of a lime). A sprue descends from the pouring cup and gates return up to the pattern in this way. The pouring cup, sprue, gates and vents can be made by coating them with Vaseline, running them under cold water, then pouring in molten wax and waiting until them hardened, then pulling the hardened wax out. They are very cheap and work perfect, but in specifically large diameters do not come [14].

4.11.1.5 Attach sprue, gates and a pouring cup

Welding the wax pieces together needs some practice so this step is a little bit complicated. If the weld seems be weak, by increasing it with thin slivers of wax which are warmed by holding in your hand can improve the strength of the weld. For blending these slivers in was can used a heated wax tool [14].

4.11.1.6 Insert core pins

For setting the core (or hollow center) of the pattern in place after the wax melts out are used Core pins. Improper use of them is that can be ruined the casting. Better use silicon bronze boating nails which have hatch marks in them to keep the pins in the plaster [14].

4.11.1.7 Assemble with board and flask

First of all select a suitably sized steel flask which will be required an inch of clearance around the pattern and between the tip of the sprue and the top of the flask. After that by the pouring cup fasts the sprue, gate pattern assembly to a piece of Masonite or plywood. It will be required to melt the pouring cup onto the board so it sticks. A board with a rough surface (such as Masonite) works the best [14].

4.11.1.8 Invest

This is when the mix 30-30 (or plaster Satin Cast, which is much finer but also much more expensive) is mixed with water and is poured it around wax pattern [14].

4.11.1.9 Burn out

The mold is then subjected to a burnout, which heats the mold between 870 °C and 1095 °C to remove any moisture and residual wax, and to sinter the mold. Sometimes this heating is also used as preheat, but other times the mold is allowed to cool so that it can be tested. If any cracks are found they can be repaired with ceramic slurry or special cements. The mold is preheated to allow the metal to stay liquid longer to fill any details and to increase dimensional accuracy, because the mold and casting cool together [14].

4.11.1.10 Pour

The investment mold is then placed cup-upwards into a tub filled with sand. The metal may be gravity poured, but if there are thin sections in the mold it may be filled by applying positive air pressure, vacuum cast, tilt cast, pressure assisted pouring, or centrifugal cast [14].

4.11.1.11 Break open

The shell is hammered, media blasted, vibrated, waterjeted, or chemically dissolved (sometimes with liquid nitrogen) to release the casting. The sprue is cut off and recycled. The casting may then be cleaned up to remove signs of the casting process, usually by grinding [14].

5 Effect of vibration on Casting

Generally, the movement of the particles of an elastic body or medium in periodically opposite directions from the position of equilibrium, periodically in time is vibration.

5.1 Ultrasonic Vibration

A lot of researcher for behavior of the melt has utilized ultrasonic vibrations. Eskin exhibited the effect of ultrasonic behavior on light alloys [15, 16]. Works of different researchers show that for cavitation, degassing of melt, fine filtration of melts (the USFIRALS process), and non-dendritic solidification, enhanced semi -solid deformation, spatial solidification and for the manufacture of aluminum alloys with low-solubility components can be utilized ultrasonic vibrations [15]. Xn *et al* [17] understood that for degassing aluminum melts, ultrasonic treatment is an impressive technique. Also Jian, *et al* revealed that for refine eutectic silicon, ultrasonic vibrations could be utilized in hypoeutectic Al-Si alloys [18]. Figure 12 reveals the effect of ultrasonic vibration on the morphology of eutectic Si. Figure 13 exhibits the influence of ultrasonic vibrations on the grain structure of A356 alloy.

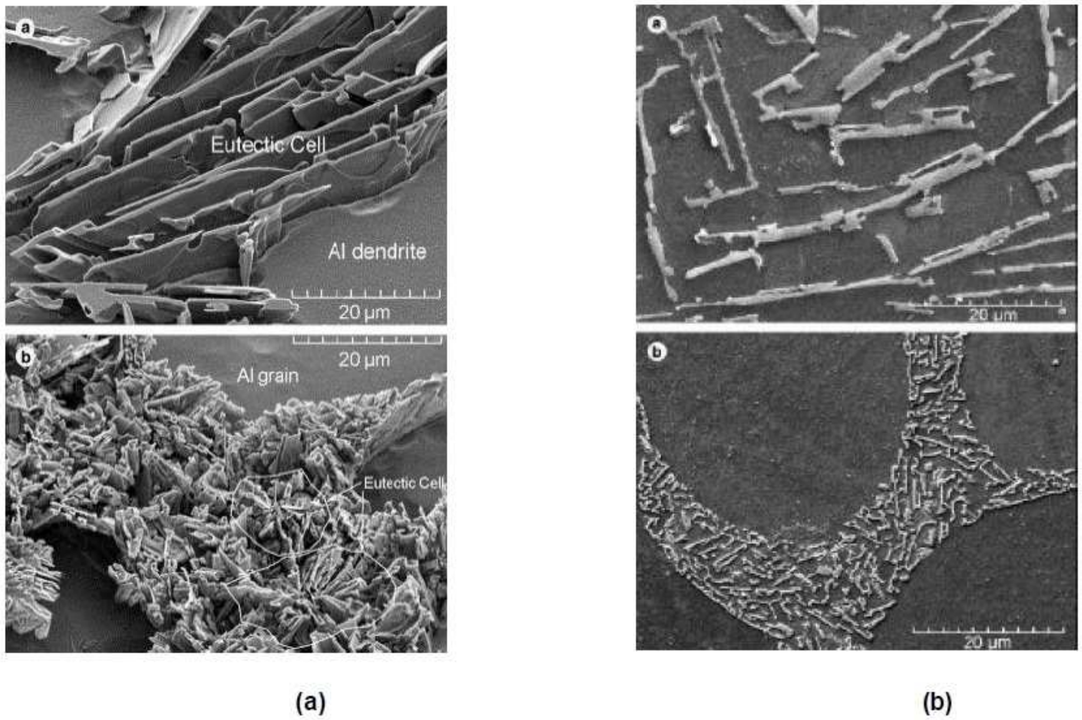

Figure 12 Eutectic Si Morphology (a) without ultrasonic vibration and (b) with ultrasonic vibration

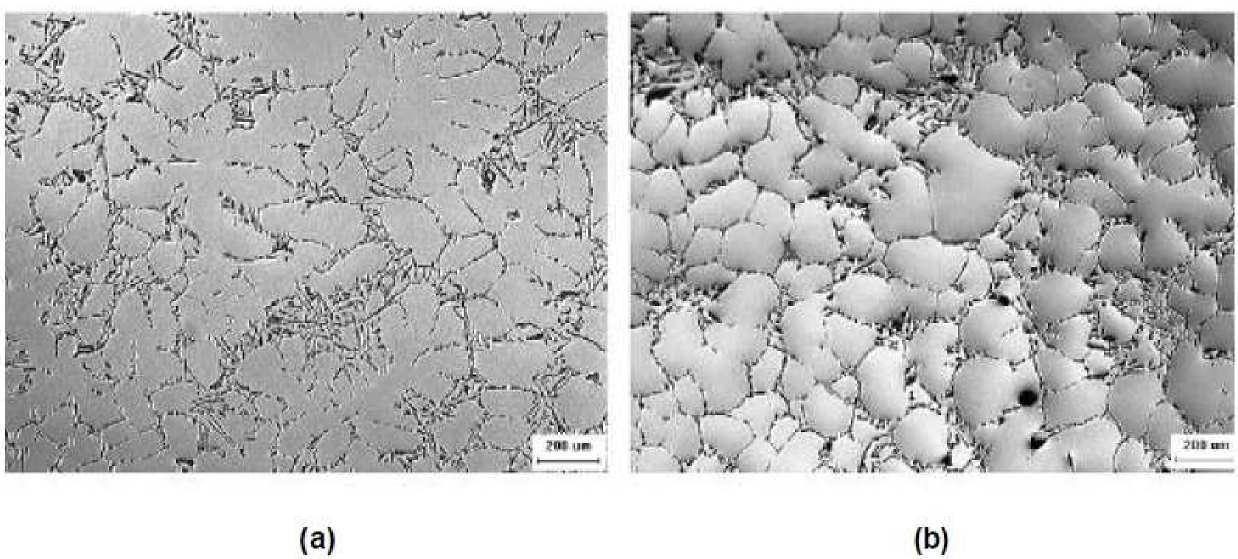

Figure 13 Effect of ultrasonic vibration on microstructure of A356 alloy, without (a) and with (b) ultrasonic vibration

For solidification characteristics of aluminium alloys ultrasonic vibration have exhibited desirable effect [19].

5.2 Electro-magnetic Vibration

Electro-magnetic vibration typically includes two different forces field:
1. A stationary magnetic field
2. An alternating electric field.

Force influence of vibrating electromagnetic body with a density ***F=J×B*** is caused inside the melt If a stationary magnetic field with a magnetic flux density ***B*** and an alternating electrical field with a frequency ***F*** and current density ***J*** is used to melt. This force puts the particles inside the melt into vibration motion with a frequency equal to the frequency of alternating electrical field, vibrating perpendicular to the plane of ***J*** and ***B*** [20]. Another electro-magnetic force is created inside the melt because of the utilized magnetics force and the caused force. This force is partly rotational and stirs the melt [45]. Fatigue 14 illustrates the relationship between these forces.

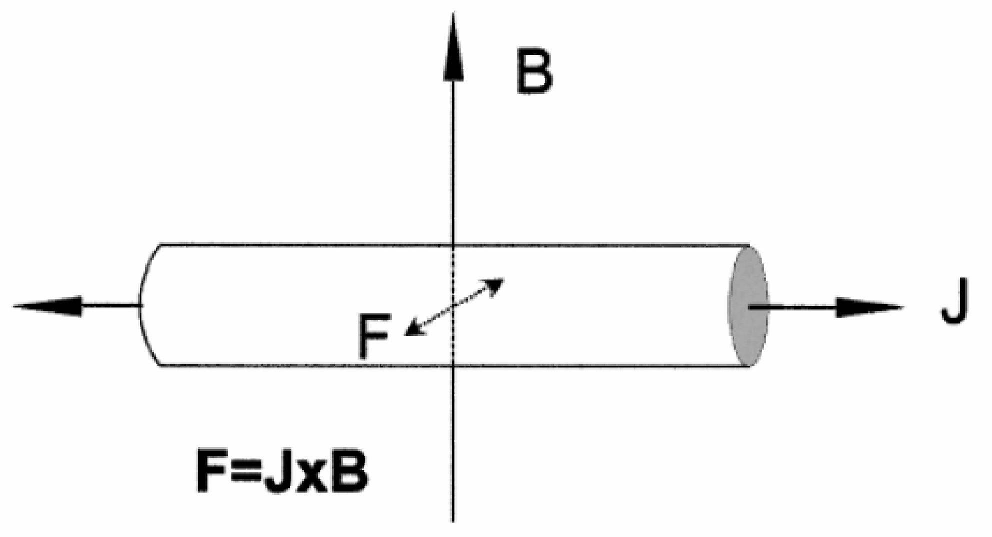

Figure 14 Direction of vibration force ***F*** developed by the interaction of the alternating electric field ***J*** and the stationary magnetic field ***B.***

Zong [20] exhibited that for remove micro segregation, and to prevent cracks and enhance the as cast surface quality to alloys, low frequency electromagnetic vibrations could be utilized to grain refine. Yoon *et al* [22] understood that the grain size of primary silicon electromagnetic will be decreased by vibrations. Mizuki *et al* exhibited that enforced electro-magnetic vibrations on an AL-7wt%Si alloy with increasing the intensity of the vibrations; the primary α-Al dendrites approached a globular shape of about 25 μm in size.
The frequency of vibration increases the level of refinements [23].

5.3 Mechanical Vibrations

Mechanical vibrations are of great importance in various fields of study including fault detection [24,25] and casting. The repetitive motions called oscillations create structural movements that can reveal the hidden cracks within the metal's structure [26] or create the required patterns depending on the application of interest. Numerical approaches such as finite element method and meshless peridynamics can be applied to predict initiation and growth of these hidden cracks [27, 28]. Existence of a crack or any kind of damage can determined using SHM/NDE methods. The most common method is using wave propagation to predict the existence of a damage and its location. Khalili et al. [29-32] have developed highly efficient elements (WSFE-based UEL) and used them in predicting the location of the damage. Their report shows that their developed SHM method and UEL can successfully and efficiently detect the damage and find its location. The whole mold is fixed into vibration by means of vibration source in this method. Although the utilize of mechanical vibrations permits limited degrees of freedom to the operator, it is the most promising method of applying vibrations to solidifying melts due to its simplicity and the ruggedness of the equipment needed for including vibrations.

Definitions and Parameters

Vibration: the movement of the particles of an elastic body or medium in periodically opposite directions from the position of equilibrium, periodically in time.
Amplitude: The severity of the vibration. Amplitude can be described in several forms:

- Peak to peak
- Zero to zero
- Average Value
- Root Mean Square Value

Frequency: The number of cycles that a system will perform in a unit time. It is usually measured in Hertz (Hz) [33].
Acceleration: The rate of changing velocity with time. Goals of this work, acceleration is provided in units of gravity. Equation 1 describes acceleration to vibration amplitude and vibration frequency [34].

$$G = 0.511 * Df^2 \qquad (1)$$

Where G is the acceleration in units of gravity, D is the displacement or double amplitude, and f is the frequency of vibrations. Figure 15 is plot of equation 1 and exhibit the relationship between amplitude and frequency.

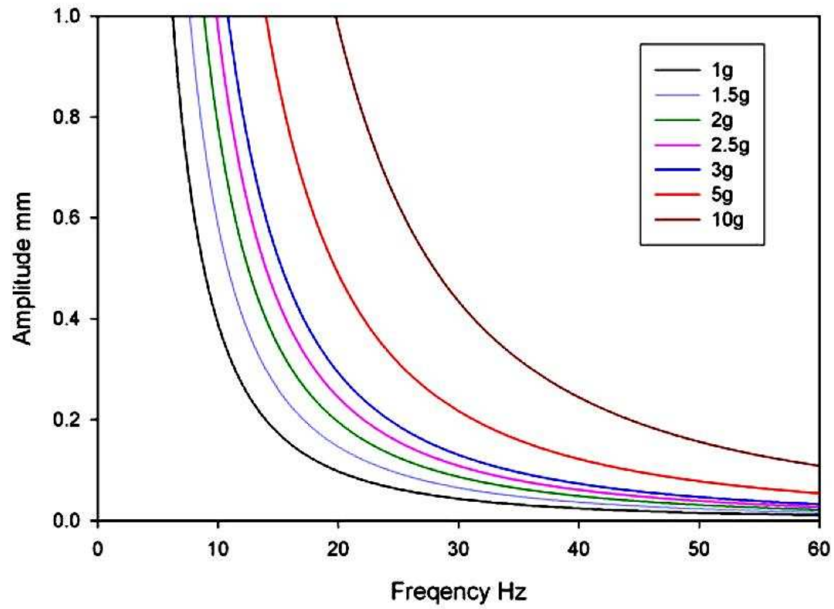

Figure 15 Relation between amplitude and frequency [51].

The Use of Mechanical Vibration in Casting

Sokoloff [35] exhibited the effect of mechanical vibrations for grain refinement in mechanical and corrosion properties of alloys. In addition, mechanical vibration has been connected to the reduction or complete removal of the leaning for pipe formation in ingots of pure metals [36]. Mechanical vibrations during solidification of NH_4Cl-H_2O cause fragmentation of the dendrites that reveals in Figure 16 [37].

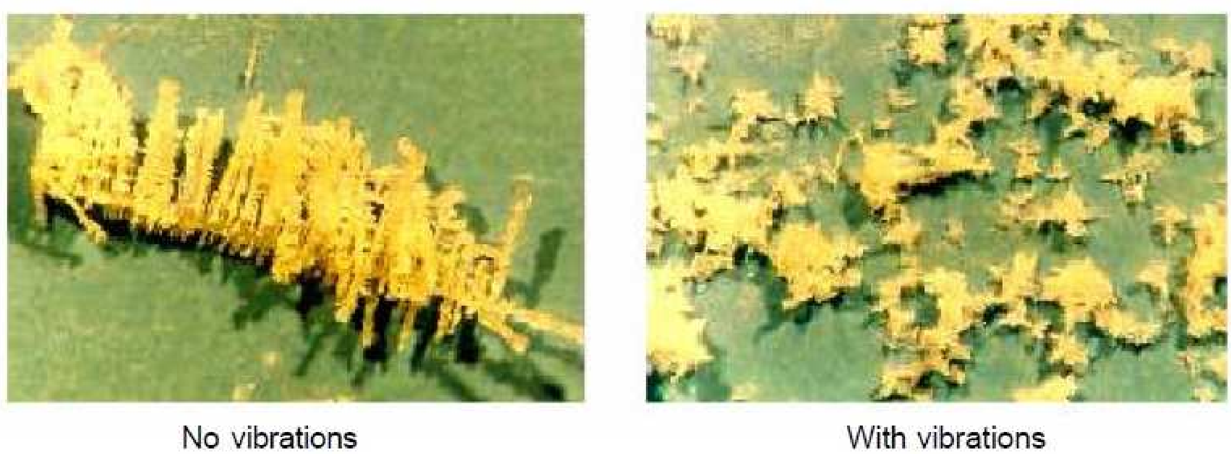

Figure 16 Dendrite fragmentation while solidification of NH_4Cl-H_2O under vibration [10].

Dommaschk *et al* [37] investigated the influence of vibrations on pure Aluminium, Al17wt%SiMg, and Al12%wtSi alloys along with other non-ferrous alloys. They concentrated on the effect of mechanical vibrations on grain refinement and mechanical

properties. They found out that the intensity of vibration increase the cooling rate and the degree of grain refinements, and grain size becomes more homogenous. The effect of mechanical on the solidification behavior of pure Aluminium is exhibited in Figure 17.
Dommaschk *et al* [38] also showed that the casting wall thickness depend on the casting characteristics could be reduced with utilizes of mechanical vibrations [37, 38]. Gharghabi et al. [39] reported that fragmentation of other structures such as, composite materials or polymer materials, might be influenced by mechanical stress and vibration caused by abrupt shocks. The simulation results presented in [39, 40] are used to validate the modeling procedure exploited in this report.

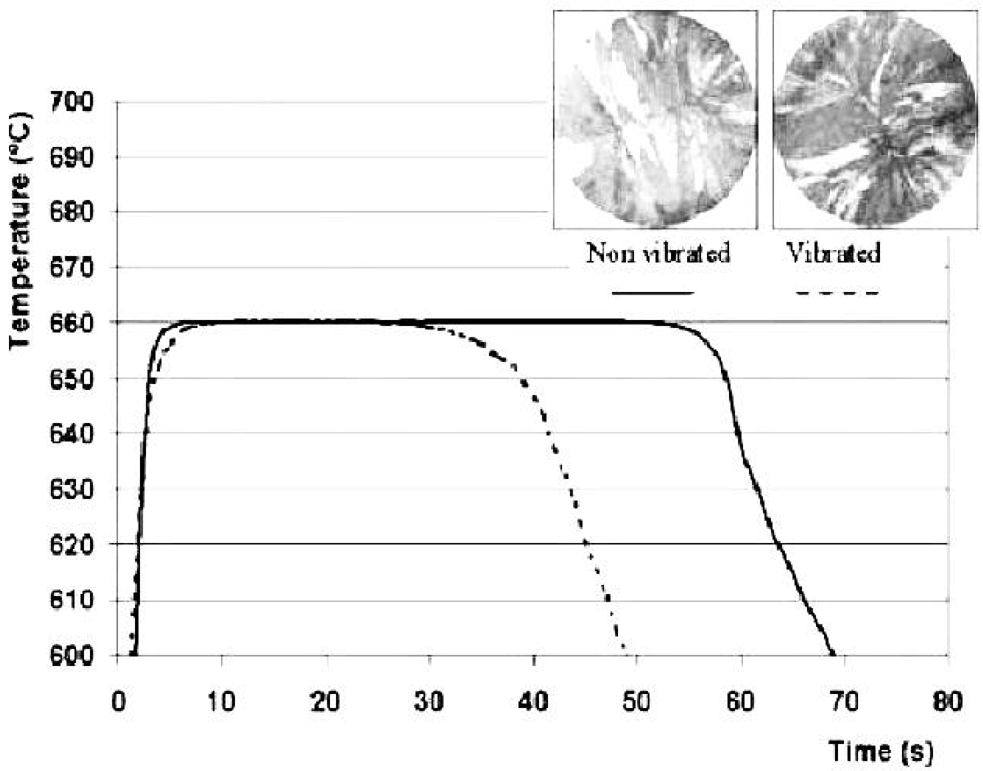

Figure 17 Effect of mechanical vibration on the cooling curve of pure aluminium

Pillai *et al* utilized low frequency vibration (100 and 200 cycles per minute) to see the effect on A356 and Al2Si alloy. They revealed that the density, hardness, UTS, and elongation of the cast components enhanced by mechanical vibrations. They ascribed to these improvements by vibration the mold to improved coagulation of hydrogen bubbles and their escape from the melt brought. Thus porosity was decreased and the melt was improved the wetting of the mold walls [41]. However, the method that Pillai *et al* utilized in production foundry environment the generation of the low frequency vibrations (hand tapping and mold tilting) is highly unpractical. Kokatepe *et al* [42] used vibrations of 15 to 41.7 Hz frequency and 0.125 to 0.5 mm amplitude to Al12.3Si alloy ingots poured in graphite mold [43]. They understood that at 41.7 Hz the solidification time of the casting was decreased by 24%, pipe volume was reduced by 55%, and grain size was decreased by 52% as compared to the un-vibrated casting. See Figure 18.

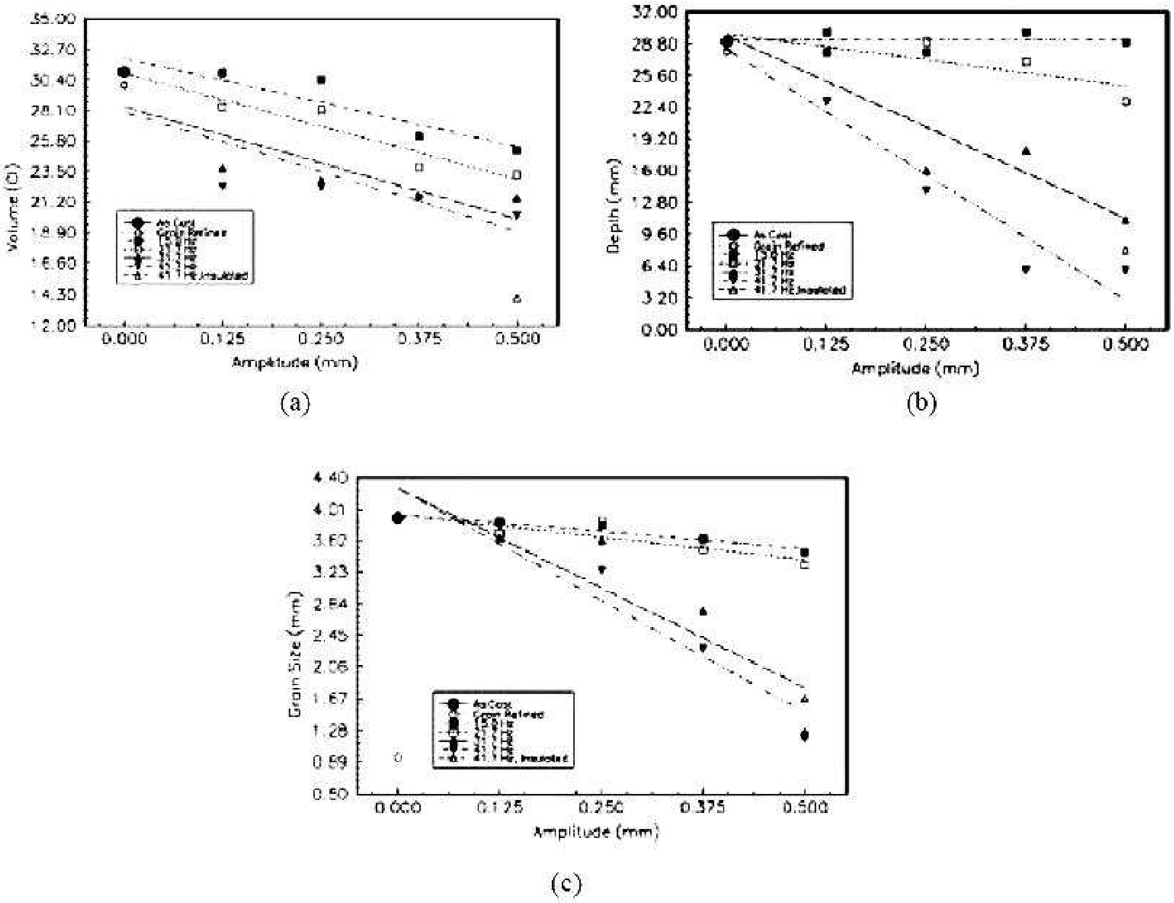

Figure 18 Effect of mechanical vibration on (a) pipe volume, (b) pipe depth, and (c) grain size of Al12.3Si ingot castings [62]

But Kokatepe *et al* [40] exhibited that the vibrations caused coarsening of the eutectic silicon because of vibrations increase in diffusivity of silicon in liquid.

Abu Dheir *et al* [41] utilized an electromagnetic shaker to deduce mechanical vibrations in a permanent mold [39, 43]. At frequencies ranging from 100 Hz to 2 kHz and amplitude ranging from 3.73 µm to 199 µm, they vibrated mold and recorded the thermal history at variant points in the mold. Their research with AA356 alloy exhibit that vibration homogenizes the temperature distribution in the mold and assist a faster cooling rate. Abu Dheir *et al* [43] saw fragmentation of the dendritic structure in Al12.5Si. They understood that the amplitude of vibration increase the degree of fragmentation Figure 19. Abu Dheir *et al* also exhibited that the vibrations including a 19 to 68 in percent increase in elongation and slight increase (3%) in UTS affected on certain mechanical properties [44,45].

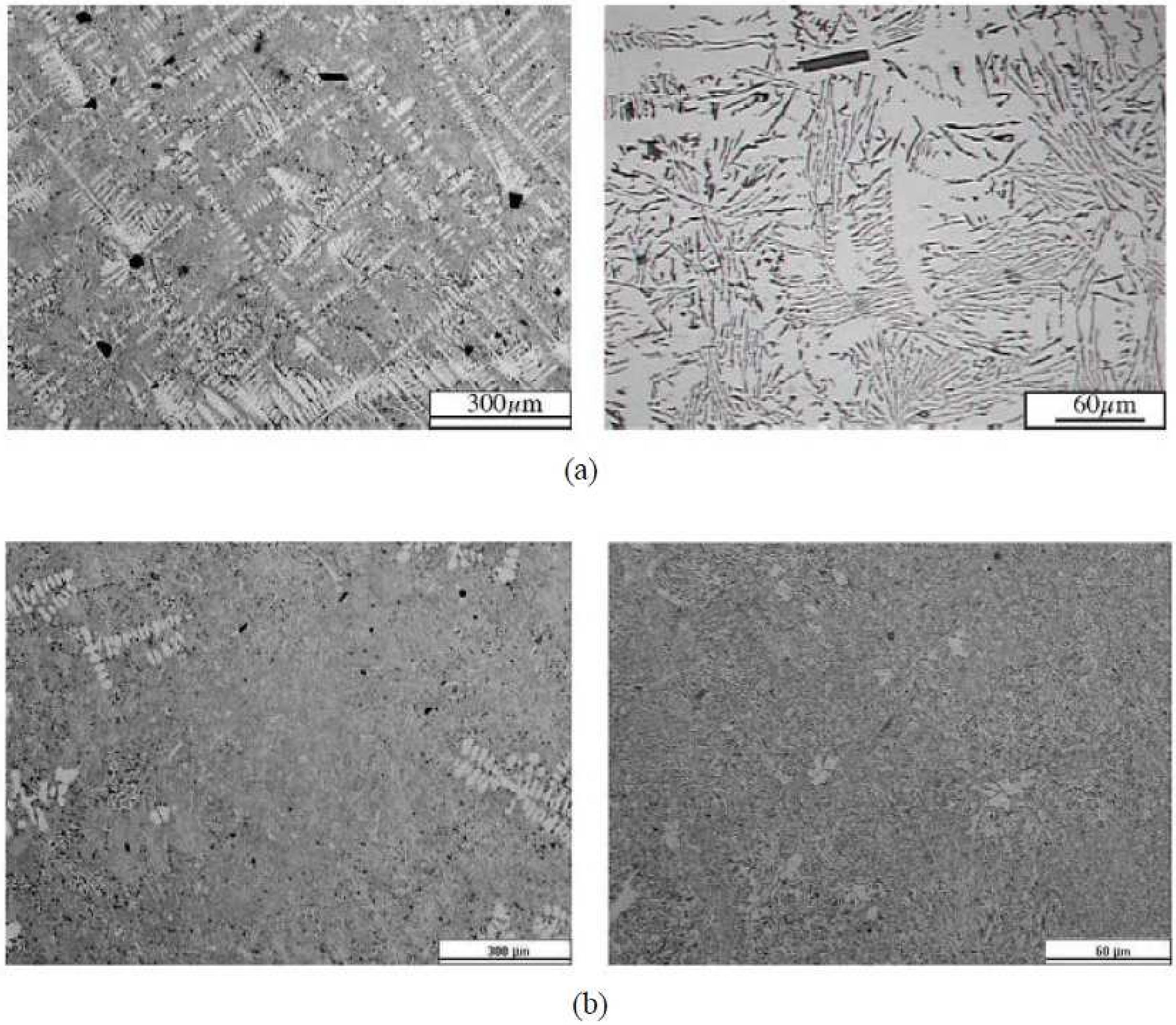

Figure 19 morphology of Eutectic Silicon (a) without vibration (b) with vibration at a frequency 100 Hz and amplitude 149 μm.

Laser Engineered Net Shaping (LENS®) is a Direct Laser Deposition (DLD) additive manufacturing technology that can be used for directly building complex 3D components from metal powders in a combined deposition/laser-melting process [46, 47]. Bagheri et al,. [48] investigated the effect of LENS process parameters, such as laser power, powder feed rate and traverse speed, on the resultant microstructure, hardness and tensile strength of Ti-6Al-4V components is experimentally investigated. Farhatnia et al,. [50-51] studied buckling analysis of functionally graded (FG) thick beam under different conditions is presented [52]. Based on the first order shear deformation theory, governing equations are obtained for Thimoshenko beam which is subjected to mechanical loads. In functionally graded materials (FGMs) the material properties obeying a simple power law is assumed to vary through thickness. In order to solve the buckling differential equations, Generalized Differential Quadrature Method (GDQM) is employed and thus a set of eigenvalue equations resulted. For solving this eigenvalue problem, a computer program was developed in a way that the influence of different parameters such as height to length ratio, various volume fraction functions and boundary conditions were included. Non-dimensional critical stress was calculated for simply-simply, clamped-simply and clamped-clamped supported beams. The results of GDQ method were compared with reported results from solving the Finite element too. The comparison showed the accuracy of obtained results clearly in this work.

6 References

[1] S.M. Afazov, A.A. Becker, T.H. Hyde “FE prediction of residual stresses of investment casting in a bottom core vane under equiaxed cooling” Journal of Manufacturing Processes, 13 (2011), pp. 30–40.

[2] H. Norouzi, S. Abedi, R. Jamalzadeh, M. Ghiasi Rad, S.H. Hosseinian “Modeling and investigation of harmonic losses in optimal power flow and power system locational marginal pricing” Energy Journal, 68 (2014), pp. 140-147.

[3] M. Ghaisi Rad, M. Rahmani, P. Gharghabi, A. Zoghi, S.H. Hosseinian “Scheduling a Wind Hydro-Pumped-Storage Unit Considering the Economical Optimization” American Journal of Electrical and Electronic Engineering, 5 (2017), pp. 16-22.

[4] H. Jouybari-Moghaddam, S.H. Hosseinian, B. Vahidi, M. Ghiasi Rad “Smart control mode selection for proper operation of synchronous distributed generators” 2nd Iranian Conference on mart Grids, Iran (Islamic Republic of), (2012), pp. 1-4.

[5] S. M. Jafari-Shiadeh and M. Ardebili, "Analysis and comparison of axial-flux permanent-magnet brushless-DC machines with fractional-slot concentrated-windings", Proc. 4th Annu. Int. Power Electron., Drive Syst., Technol. Conf., pp. 72-77, 2013.

[6] S Jafarishiadeh, M Ardebili, A Nazari Marashi, “Investigation of pole and slot numbers in axial-flux pm bldc motors with single-layer windings for electric vehicles,” 24th Iranian Conference on Electrical Engineering (ICEE), pp. 1444-1448, 2016.

[7] V.M. Aleksandrov, B.A. Kulakov, A.A. Solodyankin “Increasing the strength and reducing the chemical activity of ceramic moulds” Soviet Casting Technology, 4 (1988), pp. 41–45.

[8] S.O. Barnett “Investment casting—the multi-process technology” Foundry Trade Journal, 11 (3) (1988), pp. 33–37.

[9] M. Bakhtiary-Noodeh, S. Moradian, and Z. Ranjbar, “Improvement of the edge protection of an automotive electrocoating in presence of a prepared epoxy-amine microgel” Progress in Organic Coating, 103 (2017), pp. 111–125.

[10] M.T. Jovanovic, B. Dimcic, I. Bobic, S. Zec, V. Maksimovic “Microstructure and mechanical properties of precision cast TiAl turbocharger wheel” Journal of Materials Processing Technology, 167 (2005), pp. 14–21.

[11] S. Kalpakjian, S. Schmid “Manufacturing Processes for Engineering Materials” Pearson Education Incorporation (2008).

[12] M. Masoomi, N. Shamsaei, X. Gao, S. M. Thompson, A. Elwany, L. Bian, N. Shamsaei, L. Bian, and A. Elwany, “Modeling, simulation and experimental validation of heat transfer during selective laser melting,” in ASME (2015) International Mechanical Engineering Congress & Exposition, 2015.

[13] M. Masoomi, S. M. Thompson, N. Shamsaei, A. Elwany, and L. Bian, “An experimental-numerical investigation of heat transfer during selective laser melting,” in 26th International Solid Freeform Fabrication Symposium, (2015).

[14] E.L. Kotzin “Metal Casting and Moulding Processes” American Foundrymen Society Inc., Illinois, USA (1981).

[15] M.H. Lee, J.J. Kim, K.H. Kim, N.J. Kim, S. Lee, E.B. Lee "Effects of HIPping on high-cycle fatigue properties of investment cast A356 aluminum alloys" Materials Science and Engineering A, 340 (2003), pp. 123–129.

[16] Q. Liu, G. Sui, M.C. Leu "Experimental study on the ice pattern fabrication for the investment casting by rapid freeze prototyping" Computers in Industry, 48 (2002), pp. 181–197.

[17] Q. Liu, M.C. Leu "Fabrication of dental crowns by investment casting with rapid freeze prototyping generated ice patterns" Proceedings of the Materials and Processes for Medical Devices Conference (2003), pp. 438–443.

[18] Q. Ming, M.C. Leu, V.L. Richards, S.M. Schmitt "Dimensional accuracy and surface roughness of rapid freeze prototyping ice patterns and investment casting metal parts" International Journal of Advanced Manufacturing Technology, 24 (2004), pp. 485–495.

[19] A. Mitchell "New casting directions for gas turbine construction" Proceedings of the 24th BICTA Conference on Investment Casting, Oxford, 1999.

[20] S. Norouzi, A. Shams, H. Farhangi, A. Darvish "The temperature range in the simulation of residual stress and hot tearing during investment casting" Proceedings of the World Academy of Science, Engineering and Technology, vol. 58 (2009), pp. 283–289.

[21] O.G. Ospennikova, L.V. Pikulina, L.M. Antipin "Application of a hydrolyzed ethyl silicate in investment casting" Neorganicheskie Materialy, 46 (5) (2010), pp. 633–635.

[22] A.L. Pilchak, D.M. Norfleet, M.C. Juhas, J.C. Williams "Friction stir processing of investment-cast Ti–6Al–4V: microstructure and properties" Metallurgical and Materials Transactions A, 39 (2008), pp. 1519–1524.

[23] B. Previtali, D. Pocci, C. Taccardo "Application of traditional investment casting process to aluminium matrix composites" Composites Part A, 39 (2008), pp. 1606–1617.

[24] A. Mojtahedi, M.L. Yaghin, Y. Hassanzadeh, F. Abbasidoust, M.M. Ettefagh and M.H. Aminfar "A robust damage detection method developed for offshore jacket platforms using modified artificial immune system algorithm" China Ocean Engineering, 26 (2012), pp. 379-395.

[25] F. Abbasi, and J. Mohammadpour "Nonlinear model order reduction of Burgers' equation using proper orthogonal decomposition" In American Control Conference (ACC), 2015, pp. 583-588.

[26] F. Abbasi, J. Mohammadpour, R. Tóth, and N. Meskin "A Bayesian approach for model identification of LPV systems with uncertain scheduling variables" In Conference on Decision and Control (CDC),2015, pp. 789-794.

[27] A. Yaghoobi, and M.G. Chorzepa. "Meshless modeling framework for fiber reinforced concrete structures." Computers & Structures 161 (2015), pp. 43-54.

[28] A. Yaghoobi, and M.G. Chorzepa, S.S, Kim, and S.A. Durham. "Mesoscale Fracture Analysis of Multiphase Cementitious Composites Using Peridynamics." Materials 10.2 (2017), pp. 162.

[29] Khalili A., Jha R., Samaratunga D. "The Wavelet Spectral Finite Element-Based User-Defined Element in Abaqus for Wave Propagation in One-Dimensional Composite Structures" Simulation: Transactions of the Society for Modeling and Simulation International, January 23, 2017, DOI: 10.1177/0037549716687377

[30] Khalili A., Jha R., Samaratunga D. "Spectrally Formulated User-Defined Element in Conventional Finite Element Environment for Wave Motion Analysis in 2-D Composite Structures" European Journal of Computational Mechanics, 25 (6), 2016, pp. 446-474, DOI: 10.1080/17797179.2016.1253364

[31] Khalili A., Jha R., Jayakody N. "Structural Health Monitoring of Skin-Stiffener Composite Structures Using WSFE-based User Defined Elements in Abaqus" 25th AIAA/AHS Adaptive Structures Conference, Grapevine, TX, US, 9-13 January 2017. DOI: 10.2514/6.2017-1677

[32] Jayakody N., Jha R., Khalili A. Samaratunga D. "Assessment of Bonded Joint Health Status using Wavelet Spectral Finite Element" 25th AIAA/AHS Adaptive Structures Conference, Grapevine, TX, US, 9-13 January 2017. DOI: 10.2514/6.2017-1676

[33] Masoomi, M. "Model Development and Load Analysis of an Offshore Wind Turbine." PhD diss., University of Toledo, 2014.

[34] M.M.A. Rafique, J. Iqbal "Modeling and simulation of heat transfer phenomena during investment casting" International Journal of Heat and Mass Transfer, 52 (2009), pp. 2132–2139.

[35] S.A.M. Rezavand, A.H. Behravesh "An experimental investigation on dimensional stability of injected wax patterns of gas turbine blades" Journal of Materials Processing Technology, 182 (2007), pp. 580–587.

[36] M. Sahoo, L.V. Whiting, D.W.G. White "Control of underside shrinkage in zinc–aluminum foundry alloys by the addition of trace elements" AFS Transactions, 93 (1985), pp. 475–480.

[37] Y.K. Shen, J.J. Liu, C.T. Chang, C.Y. Chiu "Comparison of the results for semisolid and plastic injection moulding process" International Communications in Heat and Mass Transfer, 29 (1) (2002), pp. 97–105.

[38] P.K. Sung, D.R. Poirier, S.D. Felicelli, E.J. Poirier, A. Ahmed "Simulations of microporosity in IN718 equiaxed investment castings" Journal of Crystal Growth, 226 (2001), pp. 363–377.

[39] P. Gharghabi, J. Lee, M. S. Mazzola, and T. E. Lacy Jr., "Development of an Experimental Setup to Analyze Carbon/Epoxy Composite Subjected to Current Impulses," Am. Soc. Compos. Thirty-First Tech. Conf., 2016.

[40] P. Gharghabi, P. Dordizadeh B., and K. Niayesh, "Impact of Metal Thickness and Field-Shaper on the Time-Variant Processes during Impulse Electromagnetic Forming in Tubular Geometries," Journal of the Korean Physical Society, vol. 59, no. 61, 2011, p. 3560-3566.

[41] S. Tascioglu, N. Akar "A novel alternative to the additives in investment casting pattern wax compositions" Materials & Design, 24 (2003), pp. 693–698.

[42] G.K. Upadhya, S. Das, U. Chandra, A.J. Paul "Modelling the investment casting process: a novel approach for view factor calculations and defect prediction" Applied Mathematical Modelling, 19 (1995), pp. 354–362.

[43] E.C. Santos, M. Shiomi, K. Osakada, T. Laoui "Rapid manufacturing of metal components by laser forming" International Journal of Machine Tools & Manufacture, 46 (2006), pp. 1459–1468.

[44] M. Babaei, J. Shi, N. Zohrabi, and S. Abdelwahed, "Development of a hybrid model for shipboard power systems," in Electric Ship Technologies Symposium (ESTS), 2015 IEEE. IEEE, 2015, pp. 145– 149.

[45] M. Babaei, M. Babaei, and M. Niasati, "Parametric analysis of over voltages caused by back-flashover in siah-bishe 400kv g is substation," in Electric Power and Energy Conversion Systems (EPECS), 2013 3rd International Conference on. IEEE, 2013, pp. 1–6.

[46] Masoomi, Mohammad. "Numerical modeling of thermal effects during selective laser melting." In 10th Mississippi State Conference on Differential Equations and Computational Simulations. 2014.

[47] Masoomi, Mohammad, Scott M. Thompson, Nima Shamsaei, and Linkan Bian. "Effects of Inter-Layer Time Interval on Temperature Gradients in Direct Laser Deposited Ti-6Al-4V."

[48] Bagheri, A., Shamsaei, N., Thompson, S.M., 2015. Microstructure and Mechanical Properties of Ti-6Al-4V Parts Fabricated by Laser Engineered Net Shaping V02AT02A005. doi:10.1115/IMECE2015-51698.

[49] Farhatnia, F., Bagheri, M.A., Ghobadi, A., 2012. Buckling Analysis of FGM Thick Beam under Different Boundary Conditions Using GDQM. Adv. Mater. Res. 433–440, 4920–4924. doi:10.4028/www.scientific.net/AMR.433-440.4920.

[50] Farhatnia, F., Bagheri, A.M., Ghobadi, A., 2010. Buckling Analysis of Functionally Graded Timoshenko Beam, in: 16th International Conference on Composite Structures (ICCS), Porto, Portugal.

[51] Bagheri, A., Doni, Z., Toptan, F., Alves, A.C., Ramalho, A., Gomes, J.R., Silva, F.S., 2013. The effect of alumina particle geometry on wear resistance of hot pressed CoCrMo-Al2O3 composites, in: Materiais 2013, Symposiums & Coordinators - SPM.

[52] W. Li, M. Bakhtiary Noodeh, N. Delpouve, J-M Saiter, L. Tan, and M. Negahban, "Printing continuously graded interpenetrating polymer networks of acrylate/epoxy by manipulating cationic network formation during stereolithography" Express Polymer Letters, 10 (2016), pp. 1003-1015.