OPTIMIZATION OF QUALITY AND PRODUCTIVITY OF ZINC ALLOY CASTINGS BY USING ADVANCED SIMULATION TECHNIQUES

BY

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Dedication

Dedicated to my beloved ***Parents*** *and* ***my Family****, who have always been my nearest ones, so close to me that I found them with me whenever I needed. It is their presence in my heart and mind which motivates me to complete my Masters far from my home country. It is their unconditional love and support that motivates me to set higher goals in life and then work untiringly to achieve them. They supported me whenever I needed even in the worst scenarios with their strong and gentle soul which taught me to trust in ALLAH (ﷻ) and to believe in hard work and myself.*

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ABSTRACT

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The quality of metal castings mainly relies on the casting system design, material properties and several casting parameters (pouring time, temperature, and filling velocity). Optimization of these parameters is essential in order to get high-quality cast product. TEKALOY ZA-I (modified Zinc based Zamak alloy) is found to have comparatively higher thermal shrinkage values, making this alloy more susceptible to the thermal defects during casting. Due to relatively lower fluidity, this alloy requires higher external pressures to cast, making it suitable for pressure die casting and spin casting applications. Advanced Simulation techniques are found to be the best alternative as compared to the conventional expensive and time-consuming trial and error methods in the foundries. By providing on the spot, near to actual detection of defects, casting simulation tools provide ease in monitoring and timely changes in the casting system design to get a sound casting. In this study Advanced Casting Simulation tool MAGMA$^{5®}$ has been utilized to have optimum parameters for getting sound TEKALOY ZA-I alloy castings with critical geometry. For validation of simulated results, test parts have been cast by using Sand Casting, Plaster Mold Casting, 3D Z-Printed Ceramic Mold Direct Metal Casting processes. Spin Casting have also been carried out in order to have material properties achieved by recommended practice. Due to absence of computer simulation software for the optimization of spin cast product quality, two predictive models have been developed using Multiple Regression method in order to propose the design solutions. Furthermore, comparative study of gravity casting methods with Spin Casting has been conducted using different material characterization techniques and mechanical tests to get comprehensive qualitative data for all the casting processes utilized. It has been found that the plaster casting and spin casting methods are more suitable for getting high-quality TEKALOY castings, in terms of surface quality, dimensional accuracy, strength, and microstructural integrity.

ملخص الرسالة

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تعتمد جودة سبك المعادن بشكل رئيسي على تصميم نظام السبك وخواص المادة وعوامل أخرى مختصة بمتغيرات عملية السبك كوقت السكب ودرجة الحرارة وسرعة الملئ. وإذ لم يتم التحكم بهذه العوامل فإن ذلك سينعكس على حصول عيوب سطحية وداخلية في المواد المصبوبة والتي تضعف من جودتها وتماسكها. وجد الباحثون أن معدل الانكماش الحراري للخليط المعدني TEKALOY ZA-I (معدل من Zamak) عال نسبيا، وهو ما يجعله معرض لعيوب السبك وبشكل أخص الفجوات الداخلية الناتجة عن الانكماش. يمتلك هذا الخليط المعدني سيولة ضعيفة ، ولذا فإن سبكه يتطلب بذل ضغط عال في حال استخدمت تقنية القوالب للسكب أو تقنية السكب التدويري، ولأجل ذلك فإن استخدام تقنيات المحاكاة المتقدمة لتفادي عيوب السكب ولتصميم أنظمته يعد بديلاً ممتازًا عن التقنيات التقليدية المكلفة والمهدرة للوقت .ومن خلال إعطاء صورة مقاربة جدا لاكتشاف هذه العيوب، يمكن لأدوات محاكاة عملية السبك أن توفر طريقة سهلة وآنية لمراقبة التغيرات في تصميم نظام الصب، وهو ما ينتج عملية صب سليمة. هذه الدراسة استخدمت أداة متقدمة لمحاكاة للسبك (MAGMA5®) للحصول على أمثل القيم للمتغيرات للحصول على مسبوك سليم للخليط المعدني TEKALOY ZA-I وبالأبعاد الحرجة ، وذلك من خلال تحسين عملية السبك و متغيرات العملية. استخدمت عمليات السبك الرملي والسبك بقوالب الجص و الطباعة الثلاثية في قوالب السيراميك للتحقق من صلاحية نتائج المحاكاة. إلى جانب ذلك ، استخدمت عملية السبك التدويري للحصول على خصائص المسبوكات بالطريقة الموصى بها. تم تصميم نماذج توقعية للفجوات وقوة الشد للمسبوكات الناتجة من عملية السبك التدويري، إلى جانب دراسة مقارنة لعدد من عمليات السبك التدويري المعتمدة على الجاذبية مع عمليات السبك التدويري باستخدام الضغط أو بدونه للحصول على معلومات نوعية شاملة لكل عمليات السبك المستخدمة.

CHAPTER 1

INTRODUCTION

The foundry industry has been developed slowly but steadily through the centuries. At present, however, the industry is going through a process of rapid transformation, owing to modern development of new technological methods, new methods and new materials. By virtue of these changes and developments, high quality castings are produced and finished at lower costs and reaches to the customer in minimal time.

One of the basic processes of the metal working industry is the production of metal castings. Primarily, this work consists of melting metal in a furnace and pouring it into suitable sand molds, where it solidifies and assumes the shape of the mold. However, the operation of making sand castings is not simple as it seems.

Castings are used because they have specific important engineering properties; these may be economic or metallurgical. Objects amenable to casting are, in general, cheaper than forgings or weldments because patterns for molding are usually less expensive than dies, jigs and fixtures. Obviously this economy depends upon the quantity of parts to be made. If production is high enough to amortize equipment, and the part is equally amenable to manufacture by other methods, forging, welding, or some other means of fabrication may be indicated.

1.1 Metal Casting

Castings is a process in which products are produced from pouring molten metals and solidifying in the mold or die and the products achieve same shape and size of the mold. The metal poured into the pouring cup or basin at the top passes into the downsprue through the runner and enters the casting cavities through small, narrow channels called gates.

Casting is also considered as metallic part produced by solidification of a liquid metal in a mold. Castings have same shapes and dimension that of a mold." Castings do not have directional properties; no laminated or segregated structures exist, since metal is not displaced after solidification. This means that strength; ductility and toughness are equal in all directions-an important consideration in such applications as gun tubes, cylinder liners, gears, piston rings, etc.

Commercially during extraction all metals except cryogenic melting metals like mercury are generally casted to some form. Although an ingot is a casting in every sense of the word, castings, as product of the foundry, are generally considered objects made as nearly to the shape in which they are to be used as possible. Machining or grinding is usually necessary, but special casting processes can be controlled closely enough to yield castings not acquiring finishing operations; investment casting is an example.

1.2 Defects in Castings

The liquid metal solidify because of the arrangement of the atoms in a solid crystal is at a lower free energy that that of the same atoms in a liquid state. During this short time the original crystal structure of the casting is formed, the backbone upon which many properties depend. Also heat of fusion is evolved during this process which should be transferred evenly to the surroundings; failing to this causes several defects to occur. Also, in this interval, major flaws such as shrinkage porosity, hot tears, and seams can be prevented, depending upon the care with which the solidification has been planned. There are several other defects occur during casting operation. These defects can be caused by improper control and imbalance in (1) melting and pouring, (2) Gating design, (3) molding practice, (4) grain growth, (5) heat evolution and (5) transfer behavior, (6) metal flow behavior, (7) dimensional changes, (8) mold materials, (9) mold dimensions, (10) mold geometry, (11) casting geometry, (12) casting material and its (13) physical and chemical properties, (14) thermal conductivity and (15) solidification behavior, etc.

Although our emphasis throughout this study has been on methods and parameters leading to satisfactory castings, it will nonetheless be helpful to summarize typical casting defects, and to discuss causes and remedies. The defects can be grouped into two categories: those primarily due to the mold and those caused principally by liquid metal delivered at the wrong temperature or rate of transfer. We shall describe various types of defects and their possible causes briefly:

a) Porosity: This defect occurs due to dissolution of gases and air entrapment into the molten metal during the melting and pouring and then shapes as hollow spheres in solidified metal casting.

b) Shifts and Mismatch: It results from a misalignment of cope and drag, and may be due to faulty pins or poor mold assembly causes casting two halves to displace from datum reference plane.

c) Runouts: Spill–out of molten metal from mold two halves joining section caused by improper mold clamping or by an unsatisfactory sand seal between cope and drag.

d) Sand inclusions: Segregation of sand particles inside solidified casting caused by falling of the sand into the molten metal due to improper sand ramming or presence of loose sand in the mold cavity during pouring operation.

e) Core Raise: It is a term used to describe the tendency of a core submerged in liquid metal to float unless properly anchored either by the print, chaplets or cement.

f) Hot tears: It is the formation of hot cracks in semi-solid metal during or at the end of solidification due to simultaneous contraction and inadequate supply of molten metal to the casting. The contraction stresses may be large enough to cause a rupture (tearing) of the casting. It can be avoided by proper risering which ensures uniform distribution of metal.

g) Blow Holes: Gas holes below the skin of castings cause due to the presence and entrapping of gases and air inside molten metal which are unable to escape during casting operation.

h) Shrinkage Cavity/Porosity: Localized contractions in casting due to improper design of risering system incapable of feeding adequate amount of liquid metal to the casting causes the formation of microporosity called *shrinkage porosity*.

i) Gas Porosity: Formation of voids in metal due to dissolution of gases during cooling.

j) Misruns: Improperly filled corners and mold cavities are called *misruns*.

k) Cold Shuts: Defects at the junction of the two metal streams solidified at various time and temperatures cause improper fusion of metal at the junction.

l) Hotspots: Localized cavity formation due to gross shrinkage effect most likely to occur in isolated sections called *hotspots* which are the last regions of cavity to solidify.

1.3 Types of Casting Processes

A casting process, for commercial success, may depend upon speed of production, improved smoothness of casting surface and/or dimensional accuracy or upon some particular feature of special interest to the arts or professions. For example, die and permanent mold casting are appealing because of high production rates and because the molds in which castings are formed are not expendable; some molds are used for several thousand castings. Processes of casting can be classified into several categories as:

- Sand Mold Casting
- Ceramic Mold Casting
- Investment casting
- Permanent mold casting
- Die-Casting
- Centrifugal Casting

Upcoming sections describe each casting process in details with their detailed procedures, products features and process limitations. Process details of the utilized casting processes will be discussed in the experimentation section.

1.4 TEKALOY vs. ZAMAK Alloy

Zinc–Aluminum alloys are amongst the most commonly utilizing zinc alloys, used as a substitutive material with steel, copper and aluminum alloys [1] and are prominent among scientists due to their adaptability of alloy modification by adding range of elements including copper, magnesium and silicon, which can provide diversified properties and applications with enhanced mechanical, wear and corrosion resistance. These are the main attractions which emphasizes several research studies to be focused on these alloys in the last four decades [2-6]. The addition of copper and magnesium in the Zn-Al alloys leads another series of Zn Alloys categorize as Zamak. TEKALOY ZA-I is a modified version of ZAMAK with minimal enhanced properties including castability and is more suitable for spin casting operations, while ZAMAK alloys are designed for die casting processes due to lower fluidity.

1.4.1 Specifications

ZAMAK is an eutectic alloy system of Zinc-a low melting metal, this alloy is composed of mainly Zinc, Aluminum, Magnesium, and Copper (Kupfer in German) as major alloying additions, with the nominal mass percentage composition of some other alloying elements like 3 to 5% Aluminum, 0.15-3.2% copper and 0.0025-.006% Magnesium. While TEKALOY ZA-I have a nominal composition of 3% Aluminum, 3% Copper, and 0.03% Magnesium. For the simulation of casting processes ZAMAK was selected as the closest available alloy compositions in the built-in database of the software while in spin casting TEKALOY ZA-I has been utilized.

The alloy material used in this study is TEKALOY ZA-1 which is a commercial grade, low cost spin castable zinc-Aluminum-Copper-Magnesium alloy having the following chemical composition:

Table 1 Nominal composition of TEKALOY ZA-1 Alloy

Zn%	Al%	Cu%	Mg%	Pb%	Ni%
93	3	3	0.3	0.003	0.0003

The copper in compound formation with Zinc serves as nuclei during the first formation of “skin” during the solidification process in order to give you a fine grain smooth surface. Aluminum in combination with Zinc and Magnesium form the required “paste” range for the gradual release of energy as the alloy is solidifying which provide the ideal combination widening the alloys solidification range for improved metal flow and smoother surface finish.

Various kinds of die casting products are manufactured by the zinc alloys because of the low cost of the material and tooling, together with the fact that little machining is needed. Furthermore, by use of these alloys, complex shapes may be made in one piece, surfaces are smooth and can be plated easily, dimensions can be held to close tolerances, and the physical strength of the product is satisfactory in many applications.

1.4.2 Physical and Mechanical Properties

The TEKALOY ZA-I specifically the ZAMAK alloy is found to be a combination of the several mechanical, physical (Table 2) and metallurgical properties including relatively higher fluidity than other zinc alloys, low melting point, good strength, low fusion temperature, low coefficient of friction, fatigue strength, good surface finish, good corrosion resistance, and high wear resistance [7]. These properties make this alloy suitable for many industrial applications [8]. The prominent alloys are Zamak 1 to 7, having desirable properties for processing mostly these alloys are used as high pressure die casting alloys while some for conventional gravity casting techniques. But due to high shrinkage in these alloys pressure casting methods are more feasible than conventional gravity casting methods. The tensile strength of zinc-base die castings may reach 50,000 psi, and their elongation sometimes is as high as 15%.

Table 2 Material Specifications for TEKALOY ZA-1 Alloy

Properties	Nominal Values	Experimental Values
Melting Range	388 – 420°C	400°C approx.
Specific Gravity	6.75	6.78
Density	6.78 gm/cm^3	6.76 gm/cm^3
Thermal Expansion	26.5 x 10^{-6} °C	Not tested
Ultimate Tensile Strength	324.05 MPa	335.4 MPa
Elongation	2 %	3.2 %
Specific Heat	0.105 cal/gm°C	Not tested
Hardness Value	120 BHN	152 BHN
Impact Strength	40.67 Nm	Not tested

1.4.3 Industrial Applications

Owing to uses of these alloys extensively in the oil and gas industry as coatings, cladding, cathodic protection Zn anodes for underground and undersea pipelines, offshore rigs and jack-up steel structures, Zamak sucker rod string in rod pumps for oil pumping, solenoid valve seats and in gas storage and supplying tanks due to high spark and wear resistance.

Besides, ZAMAK alloys are extensively used in the manufacturing of Automotive parts, Camera body, Business-Machine, and Household appliances, Kitchen Appliances, Mirror frames, Plumbing fittings, Zippers, Bathroom fixtures (faucets and shower heads), Rickenbacker guitar "R" tailpieces, Staplers, Handles, Locks and Die-cast toys, etc.

CHAPTER 2

LITERATURE REVIEW

In this modern era of inventions and discoveries, market competition is getting tough day by day. To be competitive in the market and to do profitable business it is necessary to develop and adopt advanced industrial tools and strategies which facilitate the product design and manufacturing, cost effectively. Keeping in view of the day to day variations in the customer demands and market applications, continuous development of new and improvement of prior products is vital. This requires quick and reliable solutions that help reducing the overall product lead time, production cost and quality efficiently. Over the last few decades, casting simulation softwares and rapid prototyping technology have gained popularity among the scientists [9] and the manufacturers globally. Just after their emergence in the market these technologies have been adopted industrially providing promising results in improving the product quality and manufacturing capacity meeting high customer demands with reduced lead time [10, 11]. Rapidly cast the metal using the 3D Z-Printed molds is an intelligent invention in the field of Rapid Prototyping also known as Direct Metal Casting or Rapid Casting Technology. This technique provides solutions to the problems and limitations of conventional pattern, core and runner gating system and mold making which involves troublesome and time consuming steps of sand mixing, complex machining and adjustments. Rapidly 3D Z-Printed Molds in conjunction with the Casting Simulation Software facilitates in performing intelligent and quick optimization of casting design, process and remanufacturing by using pattern-less mold making directly from CAD model minimizing the dimensional irregularities and maximizing the precision.

Optimization of the casting process using simulation software involves a sequence of simulations in successions done to find out the best possible combination of casting parameters offered to the optimized design of runner and gating system [12, 13] with adequate geometry to get a sound casting without defects. In the current study, optimization of Zamak alloy casting using Sand Casting, Ceramic Mold Casting, Plaster Mold Casting and 3D Z-Printed Mold Direct Metal Casting processes have been carried out for intricate geometry parts using MAGMASOFT® casting simulation software. Then the simulation results have been validated through experimentation [14]. Utilizing the X-Ray module of the software, casting defects like porosity, incomplete filling, and hotspot formations have also been observed during casting which have been eliminated on the spot during simulation. Major physical factors like pressure, metal fluid flow behavior and velocity have also been controlled that affects the overall casting quality. At the last section comparison of quality and integrity results of castings obtained from the above processes with the casting from Rapid Manufacturing technique called Spin the casting processes utilized.

2.1 Research Background

In the last decade the researchers have greatly contributed in the field of casting manufacturing in terms of casting productivity analysis, development, cost, lead time and improving overall casting quality. The literature have been surveyed to get a focused research topic to be worked on, the researches involved casting techniques, mold design and development, use of computerized casting simulation, and the utilizing rapid prototyping technology 3D Z-Cast technology in casting.

Numerical Simulation of die casting process for optimization of casting system design was performed in 1999 [15] which discussed the simulation of casting process for choosing best design of runner and gating systems for a thin-walled magnesium mobile spare part. Through simulation the design was optimized by careful placement of risers and open vents to facilitate the filling operation till the last portion to be filled in the mold. The design alterations suggested by the simulation software were to prevent shrinkage defects in the casting likely to happen by original design of the casting system.

A research study in which Rapid Prototyping Technology had been integrated [16] describes the design optimization of a Titanium Dental implant. Dimensional Accuracy has also been measured using Laser Technique. First the coordinates of the original dental crown was measured by 3D Laser Scanning Machine, then the measurements from Laser Digitized Geometry have been converted to CAD model. Then casting numerical simulation was performed for the investment casting process using the MAGMASOFT ® software to optimize the runner and gating system specially the sprue design. After successful simulation of the casting system design the CAD geometry was converted to STL format and wax patterns of the dental implant was made by using Model Maker II 3D Plotting System. The wax patterns were utilized for investment casting of the actual part. Porosity measurements of the final samples were carried out using X-ray Scanning. [16]

Scientists have studied to investigate the use of master patterns made by utilizing the Rapid Prototyping Technology for the Injection Molding process [17]. Two types of molding materials had been tested for molding including the sand mold and modified silicon mold. The surface quality and porosity content of the parts produced by both molding techniques has been examined. Rapid prototyping parameters have also been discussed that can affect the dimensional accuracy of the final cast product for each molding process.

Casting simulated software has been developed using the FEM method utilizing the Gaussian Elimination Method on C++ language interface in a study [18] to successfully simulating the solidification behavior of the metal in the mold. Casting of Aluminum-Silicon alloy in a metallic permanent mold and sand mold has been simulated in order to get optimized parameters with optimized casting design for sound casting. Also for the material properties predictions of casting grain structure was done by the FEM method. Also thermal analysis has been done to predict the heat flow behavior using enthalpy method.

Another study for the optimization of Permanent mold casting process have been carried out previously [19] in which a Numerical simulation software has been tested to predict the filling and solidification behavior of metal in permanent metallic molds. Thermal and heat transfer behavior have been analyzed besides the parameters to optimize the design of casting system that are necessary to eliminate the casting defects due to irregular heat flow behavior.

Optimization of pouring, runner and riser system design and improvement in overall casting yield and product cost reduction through FEM software ”ProCAST” have been carried out by researchers in the study [20]. They are predicted the shrinkage defects in castings by simulating the sand molding process through the software.

A study in which the effects of microstructural alterations within Zn–Al alloys on the corrosion behavior of coating with steel have been assessed [21]. In the study simulation of localized corrosion has been carried out using the Finite Difference Numerical Model. This model composed of field-based calculations for the electrical potential and diffusion/migration coupled to standard electrochemical equations.

Identification and optimization of casting process parameters including filling pressure, velocity, cooling and solidification behavior, localized hotspot formation, stress analysis and porosity prediction have been done in the study [22] to identify the potential effects of these parameters on the casting quality and defect formation in iron casting.

Computational Fluid Dynamics (CFD) analysis approach have been adopted by researchers [23] using the fluid flow simulation software “Flow 3D” to simulate the metal flow behavior inside the designed mold in order to prevent flow related defects in castings usually get removed by conventional hit and trial methods adopted to design multiple-gating system.

Optimization of the runner and gating system, pouring basin design to regulate the flow and temperature distribution during mold filling operation have been done in the study [24] in order to diminish the potential casting defects in the development phase through simulation. Investigation of thermal and flow behaviors and stress distribution in the casting during pouring and solidification have also been done. In this study the researchers have utilized "View Cast" casting simulation software for the optimization of casting the valve block. During optimization the single gate approach is found to be better than the multiple gate system. Also on the basis of simulation results, it was found that to prevent the shrinkage related defects it is important to control the design of the risers and chills in gating system.

Numerical simulation for optimizing the thin walled Aluminum alloy casting in a metallic permanent mold has been studied and validated by researchers and found effective in eliminating the casting defects prominently porosity and shrinkage [25] by intelligent casting system design solutions.

A physical neural network system using the MATLAB software has been developed by the scientists to analyze the filling and solidification behavior of the metal for the optimization of process parameters of High Pressure die casting process [26]. It was found that the proposed physical network provides ease of optimizing the process parameters for the Die casting operation.

In a detailed study carried out by Simranpreet et. al., (2009) [27] discussed the comparative analysis of a conventional manufacturing technique "investment casting" and a Rapid prototyping Technique "3d Z-Casting". Initially the part designing and pattern manufacturing by both techniques with the emphasis on dimensional accuracy has been deliberated for the casting made of aluminium alloy. Beside this, both processes have been compared in terms of product mechanical, metallurgical and physical properties, metallographic microstructure and radiographic images. Optimization of both manufacturing processes of Z-Casting and Investment casting processes have been done by getting best optimal process parameters on the basis of experiments, which are necessary to get sound quality casting as per international standards. Also modified materials for the 3D printing of the patters and prototypes have been utilized by infiltrating the wax and acrylate in the casting powder, and were tested for the quality of investment casting parts. As for the Z-Cast method the pattern-less mold were developed directly from CAD model through 3D printing technique. It was proposed that 3D Z-Cast technology is better in terms of processing time, complexity and the dimensional accuracy was far better and comparable to other metal casting processes and provides higher production rates with shorter lead time. [27]

In view of literature, the importance of adopting casting numerical simulation for the optimization of casting design and to get sound product and also an idea of integrating different manufacturing techniques for the ease of manufacturing processes by rapid tooling are eminent. Similar methods are adopted in this study for the TEKALOY alloy castings by deploying innovative pattern and mold design methods by using advanced simulation software MAGMASOFT ®. The computer simulation helps to predict critical casting defects including shrinkage, porosity, blow holes, and hot spot formations just right in the development phase, which saves the lead time, material and cost. The minimization and prevention from these defects are amenable by optimizing the runner and gating system design, sprue and riser design, and careful selection of their location within the mold. Moreover controlling the heat transfer behavior, filling and solidification rate and flow behavior are equally important in predicting the final quality of the casting. Porosity and shrinkage defects are found to be most common problem in the castings predicted by the simulation.

As for the flow dynamics careful designing of Gating system is crucial to prevent the turbulence in the metal flow inside the mold that is one of the causes of shrinkage and porosity formation. Pressurized gating design is suggested to be better option for casting the critical parts having thin sections. Besides, no particular information is found for optimizing the gravity casting of the die-casting Zinc alloys using the numerical simulation. An effort has been made to optimize and to obtain sound castings through gravity casting methods using such die-casting Zamak alloys which have low flowability and density not feasible for the gravity casting operations. Moreover, validating the credibility and accuracy of the optimizing results of 3D Z-Cast process pattern-less molds has been analyzed by applying integrating approach for a Computer Casting Simulation and the Rapid Prototyping Technology.

Finally the comparative study of all the castings achieved from several gravity casting methods including Sand Casting, Plaster Mold Casting and 3D Z-Cast Direct Metal Ceramic Mold Casting has been carried out in terms of dimensional accuracy, surface morphology, microstructure and other Mechanical and Metallurgical properties.

All the design and quality related methodology adopted in this study are in accordance with the data provided in the technical articles and books that provides the fundamental and in-depth information about the relevant data. These articles involves the topics including casting design, casting numerical simulation and validation of results, integration of different Rapid Prototyping techniques and final quality and integrity assessment of the castings. For the runner, risering and gating system design general practice in accordance with the Rio Tinto Inc. and JICA (Japan International Cooperation Agency) suggested standards have been adopted as the best resource for the mold designing in the foundry industry.

2.2 Research Motivation

The main motivation of carrying out this study is the achievement of critical geometry Zn–alloy casting having sound quality using different gravity casting methods (ceramic, plaster and sand casting, etc.) as well as from Spin casting, considering the fact that Die Casting is preferred when large quantity production (Greater than 10000 to 100000) is needed for such parts. If volume of production is medium (500 to 10000), Spin casting may be deployed and it is claimed that spin casting gives comparable results as die casting. If the quantity of production is limited such as 1 to 500 parts, then one should explore the possibility of using various gravity casting processes. The feasibility of using such processes in limited volume production is the ultimate focus of this work.

Beside a large number of applications of the TEKALOY (modified ZAMAK) alloy due to its several good properties, it has some serious problems in the gravity casting due to its unsuitable fluidity and high viscosity due to presence of higher temperature alloying elements. Copper forms a highly viscous $CuZn_4$ intermetallic phase in the Zn-Al matrix which reduces the fluidity of molten metal, making it unsuitable for gravity casting methods. Also, TEKALOY ZA-I alloy have higher shrinkage value nearly 6.5 as mentioned in Table 3 as compared to other ferrous metals and also the fluidity [28] of the Zamak alloy is suitable for the pressure casting processes like high pressure die casting, extrusion and TEKALOY is designed for spin casting operations. That's why the Zamak alloy is generally casted by die casting and TEKALOY by spin casting conventionally in the industries, both processes need relatively larger pressure and specifically designed heavy investment machines and equipment with expensive mold making, gravity casting processes are more attractive for low quantity production with less expensive equipment and mold making.

Table 3 Shrinkage Values of Common Metals and Alloys

Metals/Alloys	Volumetric Shrinkage (%)	Metals/Alloys	Volumetric Shrinkage (%)
Aluminum	6.6	White Iron	4-5.5
Zinc	**6.5**	1% Carbon Steel	4
Al-4.5%Cu	6.3	Al-12%Si	3.8
Copper	4.9	Carbon Steel	2.5-3
Magnesium	4.2	Gray Iron	2.5

2.3 Research Objectives

This study suggested the feasibility of using gravity casting processes such as ceramic mold casting, plaster molds casting and sand casting to make good quality TEKALOY parts without application of the external pressures/forces. This can be achieved by using Computer Casting Simulation tools to select the optimum parameters and controlling the designing and casting defects right at the designing phase. Besides this analysis and validation of the optimum casting design and processing parameters to get sound

TEKALOY castings from gravity casting processes and compare their quality with the spin cast parts are the main research objectives. The core objective mainly focused during this research study is mentioned below with the sub-objectives and the tasks accomplished to meet the core objective have been defined in detailed manner in preceding chapters.

Core Objective: To compare different quality and integrity features of TEKALOY ZA-I parts cast with gravity casting processes (ceramic, plaster and sand casting, etc.) with parts produced with spin casting process which is often deployed traditionally for medium to large quantity production of Zn Alloys if Die casting is not justified for specific conditions of quantity, quality, time and cost.

For the accomplishment of above core objectives the following methodology divided into tasks have been adopted:

- **TASK 1**: Initial mold designing to get near optimal molds using the standard industrial practices traditional approach for Zn- alloy (TEKALOY–modified Zamak) castings for various gravity casting methods (ceramic, plaster and sand casting, etc.).
- **TASK 2**: Demonstrating the feasibility of Advanced Simulation Techniques in refining a traditionally designed mold towards an improved and near perfect mold and sound quality cast product by optimizing the casting system design and process parameters using an example of a 3D printed ceramic molds casting process in minimizing the casting defects. As well as to see the feasibility of 3D Z-Printing in producing the pattern less mold in reducing the time and cost of casting. The above two tasks have been discussed in chapter 5.

- **TASK 3**: Studying the spin casting with experimentation and to explore the process capabilities and limitations of *Spin Casting* of TEKALOY (Zn-Alloy) in terms of material properties achieved from recommended practices including mold development and real-time casting. These tasks have been discussed with the methodology adopted in chapter 6 and 7.
- **TASK 3.1**: Exploring the parametric relationships amongst the process parameters of spin casting.
- **TASK 3.2**: Developing the predictive models for the quality indicators of spin casting process: for porosity and tensile strength.
- **TASK 4**: Studying quality aspects of castings reflecting the "soundness" (minimizing the surface and internal defects, porosity), and economic aspects like "higher yield" and "productivity" by using various gravity casting processes and spin casting. These tasks have been accomplished with the methodology discussed in chapter 8.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

The experimental methodology involves the steps of first selecting a suitable part to be tested for the design optimization study. Second, it involves the CAD Modeling of the test part and designing of mold by applying standard industrial practices as per Rio Tinto and JICA standards. CAD software has been utilized for 3D modeling of the part and mold. Calculated mold design was then simulated by MAGMASOFT® in successions in order to get optimum design factors and casting parameters for further design modifications to optimize the flow, filling and solidification behavior, metal velocity, pressure, and temperature at runner gates and part. Finally the optimized mold design was validated by real time casting operations using different gravity casting processes. In the last, the final castings from all the molding techniques were tested and compared for their mechanical and metallurgical properties, surface finish and dimensional accuracy. Detailed experimental sequence has been illustrated in Figure 1.

For the mechanical properties tensile test, hardness test, density and porosity measurements have been analyzed in order to judge the mechanical performance of the castings. Moreover, the material characterization techniques have been utilized to have a good knowledge about the casting material properties dependent on grain structure by using Optical and Scanning Electron Microscope, corrosion resistance by Potentiodynamic Polarization Test and Weight Loss methods and internal porosity, etc.

In conjunction with the mechanical testing and Material Characterization, to analyze the overall quality and integrity, dimensional accuracy and surface outlooks have been compared for validation of performance capabilities of each casting process and optimized product design via simulation.

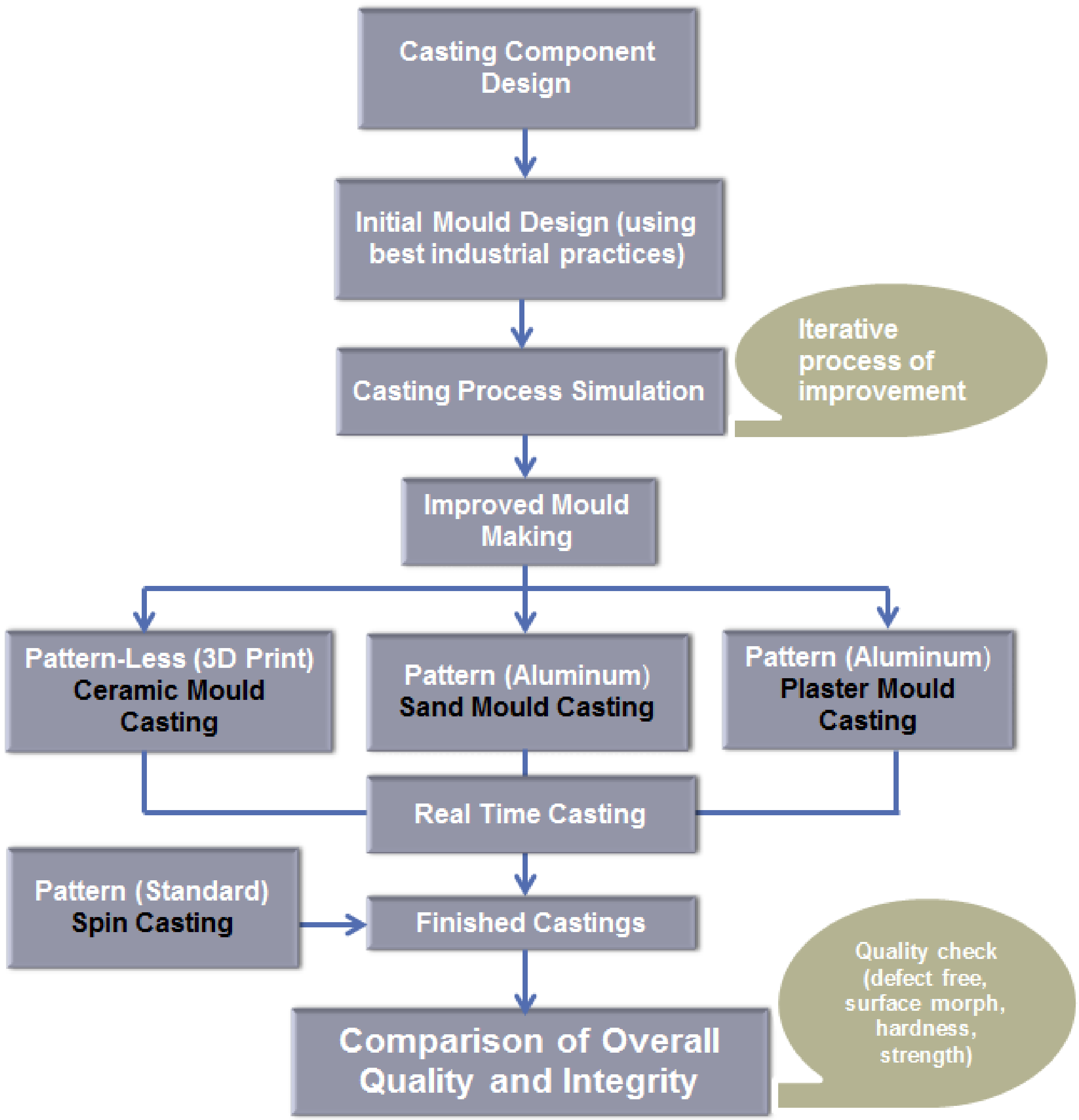


Figure 1 Experimental Sequence of Study

3.1 Selection of Test Part and CAD Modeling

In order to analyze and evaluate the process capabilities, multidimensional and multivariate geometry is to be selected. The part geometry selected for this study involves semi complex geometry consists of several dimensions with a combination of thin and thick sections with circular geometry. The part selected for the study are “Dumbbell” shaped “Tensile specimen” Figure 2, which are to be simulated to be cast using the TEKALOY ZA-1 Zinc alloy. In these parts the minimum dimension is about 3.2 mm with the maximum limit of 75 mm.

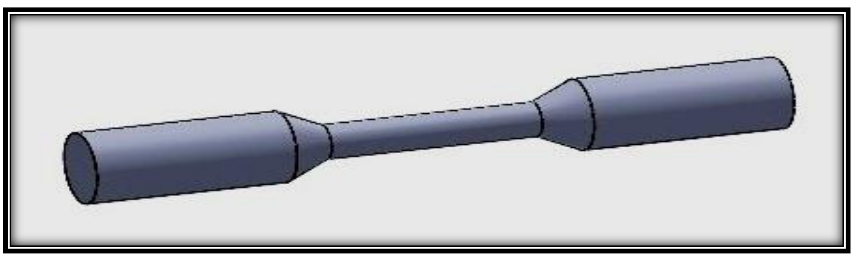


Figure 2 Test Part Geometry selected for Study

3.2 Mold Designing by Best Industrial Practices

Mold designing is the most crucial part of the metal casting process, as the whole processing and final product quality reliant upon mold making. As the mold is the essential part of casting which consists of several integrated components join together to form a complete runner and gating system, which ease the pouring and filling of the molten metal inside mold.

For designing the runner, risering and gating system general practice in accordance with the Rio Tinto Inc. [29] and JICA (Japan International Cooperation Agency) [30] suggested standards have been adopted as the best resource for the mold designing in the foundry industry. As no equations and relationships have been designed specifically for the ZAMAK or TEKALOY for the mold and casting system designing, the relationships for the cast iron and steel have been utilized for initial calculations. Which are then optimized by the simulation software itself.

Due to the fact that shrinkage phenomenon occurs during pouring and solidification of the molten metal inside the mold which are to be control through best mold casting system design. One should consider the following factors to be accommodated in the mold casting system design.

a) <u>Columnar Solidification</u>: Because of the columnar growth of the dendritic grains, planes of weakness can be developed during freezing at sharp corners, rectangular sections and perpendicular to surface junctions. So fillet and rounded corners are preferable.

b) <u>Center-line shrinkage</u>: It is occurred due the formation of columnar solidification or progressive solidification, depending on the alloy casted. This defect is an actual shrinkage defect, whereas planes of weakness may occur in sound metal depending upon the solidification mechanism of that alloy, shape factor and size of the casting sections.

c) <u>Volumetric Shrinkage</u>: When metals or alloys solidify and cool, they always contract in volume. The metal used to shrinks during casting in several phases; the liquid metal contraction after pouring, solidifying contraction during freezing, and solid metal contraction during cooling to the ambient room temperatures.

d) <u>Solidification Shrinkage</u>: Shrinkage occurs in the metal due to contraction occurs in the metal during solidification from the liquid molten state. There are two types of shrinkages in cast metals: *liquid shrinkage* and *solid shrinkage*. Liquid shrinkage takes place before the molten metal solidifies. Solid shrinkage is the contraction in the hot metal when it cools or freezing temperature to the temperature of the surrounding air. Allowance is made during the pattern making for this shrinkage.

Beside above mentioned shrinkage factors there are some issues and considerations to be take care of during the mold casting system designing. These mechanisms are directly involved in the casting process and affect the runner and gating calculations as a whole:

1. ***Solidification Mechanism and rate:*** In order to get proper design and location of the risers, the crystallization and shrinkage behavior during solidification of molten metal in the casting is required which depends upon several factors including chemical composition and the temperature variations in the mold.

2. ***Heat Transfer Mechanism:*** Application of Heat Transfer equations is necessary to predict the shrinkage porosity in the casting during the solidification. Through these relationships it becomes easier to place the proper risers on the casting to avoid shrinkage porosity.

3. ***Molten metal Flow Mechanism:*** Improper flow of the molten metal inside causes several problems including the casting defects like sand mold particles in casting due

to erosion, air related defects, gases entrapment, porosity, blow holes, shrinkage and high temperature mold erosion. Also improper solidification rate of the molten metal inside the mold cavity has been observed at undesired locations.

4. ***Stresses in metal in the solidus temperature range:*** Even though a sound casting has been obtained, the thermal gradients developed during solidification can cause serious stresses that lead to hot tears at the temperature of solidification. The thermal gradients in the casting at high temperatures can also lead to high stresses in the cold casting.

5. ***Mold Materials and production methods:*** Here it is necessary to select the most economical materials for mold construction. Which molding method will provide satisfactory castings at lowest cost.

6. ***Pressure in molds and lifting of cores:*** In foundry practice, it is the utmost importance to make provisions for offsetting the lifting force of liquid metals on the cope and for proper clamping and weighting of molds. When molten metal is poured into the mold cavity it behaves similar to other liquids and tries to maintain its level and the pressure develop in it will be exerted equally in every direction. Due to this pressure, the cope of a mold have a tendency to lift, if the lifting force (Metallostatic pressure) of the metal is greater than the weight of the cope. If a light metal like aluminum or zinc is poured into mold cavity, the weight of cope is most likely exceeds the lifting force of liquid metal, but it depends upon the mold material density, as in our case the TEKALOY ZA-1 alloy is much denser and it lifted the cope in our first casting experiment. To overcome this problem the mold two halves

must be clamped properly by using vice clamps or application of proper load over mold to prevent the cope to keep from floating when the metal is poured. Metallostatic pressure exerts a buoyant effect on the cope, which can be calculated from the following relationship:

$$F_c = P_c \times A_c \qquad \text{Eq. 3.1}$$

Where, F_c is the force pushing upon cope, P_c is the Metallostatic pressure at cope parting surface and A_c is the projected mold cavity area at cope parting surface. P_c is calculated as follows:

$$P = w \times h \qquad \text{Eq. 3.2}$$

Where, w is the weight of metal per cubic inch and h is the effective height of metal head above cope. The effective head for castings both in the cope and drag is less than the sprue above the parting line. So the total upward force can be calculated as:

$$F = \rho \times A \times h \qquad \text{Eq. 3.3}$$

Where, ρ is the density of metal in pound per cubic in., h is the sprue height in the cope. If the weight of the cope itself is subtracted from the F the additional weight required to resist static pressure is obtained which is found to be 5.8 kg. Safety factor of 1.5 to 2.0 is added to the calculated value to overcome dynamic-pressure effect.

7. **Solidification Time:** If geometrically similar castings of different sizes are poured into the same mold material, the time for complete solidification will be proportional to the square of their linear dimensions. For comparing castings of different shapes this relationship has been generalized into the form known as Chvorinov's rule [31].

Solidification Time = Constant (Volume/Surface Area)^2

or $$t = K\left(\frac{V}{A}\right)^2 \qquad \text{Eq. 3.4}$$

8. **Fluidity of Molten Metal:** The term fluidity is the ability of the metal to fill a mold. It can be calculated by using the spiral tube casting method; the extent upto which the metal is reached in the spiral tube represents the fluidity of that metal. To determine the fluidity consideration of both metal and mold properties is necessary. The metallurgical properties that affects the fluid flow behavior of metal includes: Metal composition, Superheat, Metal viscosity, Surface Tension, Surface oxide film, Adsorbed gas films, Suspended inclusions, Inclusions precipitating during freezing.

The quality of the final product depends upon intelligent planning of the pattern and mold making. As properly designed molds and patterns are essential for the production of good sand castings at the lowest possible cost. The important considerations in pattern making includes: appearance of the casting, the ease with which the casting cavity is molded and the facility with which the pattern may be withdrawn from the mold.

Since patterns are used to make the mold into which the metal is cast, so careful planning of the design of the mold and all details are essential. Among details to be considered are the shape of the mold, the number and shape of gates or channels that are intended to conduct the poured metal into the mold cavity, the number and design of risers or reservoirs for retention of surplus molten metal (loss due to normal contraction of the metal during solidification is compensated for by metal stored in these risers), and the matter of correct location of the gates and risers. [32]

Besides making the vents for escape of gases, there are Risers which are formed with the pattern just above the casting on the surface in order to remain open during the pouring of metal for the escape of the gases freely and to provide a reservoir of molten metal to compensate for the cooling shrinkage of the casting metal and for the liquid shrinkage to draw metal from the riser.

Previously discussed the solidification characteristics of metals and alloys and how these were influenced by composition and external variables. All these factors must be accounted for designing a gating system for a casting. More specifically, the shrinkage behavior and crystal growth morphology must be recognized if the gating design is to be effective. The condition of having the partially solid, partially liquid zone growing from the outside inward is what is referred to as "progressive solidification". Gating design must control this progressive solidification in such a way that no part of the casting is isolated from active feed channels during the entire freezing cycle. This is referred to as "directional solidification".

Directional solidification is the product of casting design, location of gates and risers, and the use of chills and other means of controlling the freezing process. In principle, it means that is a casting is to proportioned and disposed with respect to the feeding system that the sections most distant from the available liquid metal will solidify first, there will be a successive feeding of the contracting metal by still liquid metal until the heaviest and last to freeze section is reached. This, in turn, can be fed by extra reservoirs of metal provided for that purpose and referred to as risers, or heads. These risers, or heads, are attached to the casting at the right locations and so that they can continually supply hot liquid metal to the shrinkage casting until it is completely solidified.

Freezing would have occurred first in the small section, as before, but then there would be no liquid metal available to feed the heavier section by gravity, and would have developed a general porosity that could not be eliminated. On the other hand, additional metal provided by an extra head or riser on top of the heavy section would eliminate completely the localized shrinkage.

The design of the gating system depends upon its primary objectives. Thus a gate may be designed for ease of molding, to avoid turbulent flow, or to prevent washing of sand from the mold walls. Branch gate is adopted in this thesis work; it is designed to feed multiple castings form the single runner.

The basic starting point for any discussion of gating is a review of the principles of fluid flow for vertical and horizontal passages. These calculations are useful for estimating the pouring time of a casting. Pouring time can be calculated by the following relationship:

$$t = V/Q \quad = V/Av \; (in^3 / (in^3/sec)) \qquad \text{Eq. 3.5}$$

Where t is the total pouring time, V is the total volume and Q is the flow rate, A is the total area and the v is the velocity and for vertical Gating: $v = 27.7 \sqrt{h}$ (in/sec).

We shall first discuss the basic equations of flow and then apply them to the vertical and horizontal portions of the gating system. From elementary hydraulics, we can apply two very important principles, the *law of continuity (3.5)* and *Bernoulli's equation (3.6)*.

$$Q = A_1 v_1 = A_2 v_2 \qquad \text{Eq. 3.6}$$

Where Q is the rate of flow in cubic inches per second, A is the area in square inches and V = velocity in inches per second.

The flow of a liquid in a mold is governed by a number of other variables, best summed up in terms of Bernoulli's theorem, which states that the sum of the potential energy of the velocity energy, the pressure energy, and the frictional energy of a flowing liquid is equal to a constant. This theorem can be expressed in the following equation:

$$Z + P_v + \frac{V^2}{2g} + F = K \qquad \text{Eq. 3.7}$$

Where, Z is the pressure head, P_v is the Pressure head, $V^2/2g$ is the Velocity Head and the F is the Frictional loss of head.

Secondly all it should be recognized that liquid metal flows either in stream lined laminar fashion or in a turbulent manner. Smooth or turbulent flow depends upon the velocity of the liquid, the cross section of the flow channel, and the viscosity of the liquid. The relationship is expressed as the Reynolds's number:

$$R_n = \frac{mean\ velocity\ of\ flow\ \times\ diameter\ of\ tube\ \times\ density\ of\ liquid}{kinematic\ viscosity\ of\ liquid}$$

$$R_n = \frac{\rho V d}{\mu} \qquad \text{Eq. 3.8}$$

To find heat flow through mold, the main route of heat escape, to permit the solidification of the metal. If we can obtain a general expression for the temperature at any point x in the mold, we shall be able to calculate the heat flow and thus the freezing time of the casting.

The flux (V) of heat transmitted per unit time depends directly upon the temperature difference, the thermal conductivity, and the cross sectional area of the wall, and inversely upon the distance between the hot and cold surfaces. If we assume that conductivity (K) is independent of temperature, then:

$$J = K. \Delta T/ \Delta x \qquad \text{Eq. 3.9}$$

Where,

$J = Btu/hr.ft^2$

X= wall thickness in ft.

T = temperature difference in Fahrenheit

K = thermal conductivity in $Btu.ft/F.hr.ft^2$

When a metal is poured into the mold, most of the heat is eventually absorbed by the mold itself, whereas in the steady state case all of the heat from the inner surface is transmitted to the outer surface. For this reason, the specific heat of the mold material, (C_{mold}), the density of the mold material, ρ_{mold}, and the thermal conductivity, K_{mold}, enter the heat flow equation, and the for convenience, can be combined in one term:

$$\text{Thermal diffusivity } (\alpha_{mold}) = k_{mold} / C_{mold} \text{ x } \rho_{mold} \qquad \text{Eq. 3.10}$$

From these relations we may also determine t, the time required to freeze a given distance d, and the correlation of d with t. First, it should be noted that we can choose A as the area of one side if we take V as half the volume, and obtain the same result. Let us assume a smooth freezing front for the plate; then, we have;

$$T = Bd^2 \qquad \text{Eq. 3.11}$$

Where, B is the mold constant. Therefore the thickness solidified varies with the square root of the elapsed time. The heat flowing Q through area A in time t at the mold metal interface is:

$$Q = A.2K (T_1 - T_0) t/\alpha \qquad \text{Eq. 3.12}$$

Where, K = coefficient of thermal conductivity of mold, T_1 = interface temperature, T_0 = original mold temperature, α = coefficient of thermal diffusivity of mold.

The gating system devised to feed the casting cavity serves the dual function of delivering the metal to this cavity as well as of serving as a reservoir for the additional metal required as shrinkage takes place. In a very general way, delivery of the metal is accomplished by the gating system, whereas reserve metal is supplied by risers. [33]

Improper design of a gating system can cause one or more of the following defects in the casting:

1. Sand, slag, dross or other impurities
2. Rough Surface
3. Entrapped gases
4. Excessively oxidized metal
5. Localized shrinkage (pipe shrinkage macro-shrinkage)
6. Dispersed porosity, or microporosity
7. Incomplete fusion of liquid metal where two streams meet (cold shuts)
8. Entrapped globules of pre-solidified metal (cold shots)
9. Unfilled molds (misruns)
10. Metal penetration into sand mold.

A slight trickle of metal or metal poured too cold is undesirable because the metal would freeze too fast to fill out the mold or would develop cold shut. Very rapid filling of the mold also would present such problems as having an adequate gating system to handle a large volume of metal in a short time, erosion of the mold wall, rough surface, excessive shrinkage, and other possible defects.

In conventional sand casting, establishing the optimum pouring rate is the step in the design of the gating system. Once this is done, the next step is the proper proportioning and distribution of the various parts of the gating system in order to achieve this rate.

As the metal gains velocity in passing through the sprue, it loses its pressure energy, or head. This is demonstrated by the constriction in cross section that appears in a metal stream at pints some distance from the pouring spout. The loss of pressure head in sprue may result in a tendency to form a vortex on the metal in the sprue or a negative pressure effect in the metal column so that gas from the mold is sucked into the metal stream. The remedy is to taper the sprue opening. This also reduces mold erosion and metal turbulence.

As mentioned in the preceding section, sprue size is often selected so that it controls the pouring rate; i.e., the major restriction to flow in the gating system occurs in the sprue. This has the advantage of early establishment of the proper flow characteristics and of reducing the rate of flow of metal entering the mold cavity from the gates. The Sprue should be designed to permit enough metal to flow in the cavity. The volumetric rate of flow (Q) should be constant at any level in the sprue and the relationship between height and cross-sectional area at any point in it is given by this relation: $(A_1/A_2) = \sqrt{}h_2/h_1$

Balance of the feeding areas is expressed as Gating Ratio which is the term used to describe the relative cross-sectional area of the components of a gating system. It is usually defined as the cross-section ratio of sprue area: total runner area: total gate area. Gating Ratios may be grouped into two general classifications: pressurized and un-pressurized systems. In the pressurized system a back pressure is maintained on the gating system by the fluid flow restriction at the gates; this usually required that the total gate area be not greater than the area of the sprue, as for example in systems with gating ratios of 1:0.75:0.5, or 1:2:1. In pressurized systems, the primary restriction to fluid flow is at or very near to the sprue; gating ratios such as 1:3:3 are used for this type system. Pressurized systems are generally smaller in volume for a given metal flow rate than are unpressurized systems; thus less metal is left in the gating system and casting "yield" is higher.

For unpressurized systems it is difficult to obtain equal flow from multiple gates. As with the step-gates, the kinetic energy of the flowing metal in unpressurized systems tends to carry it down the length of the runner and out the gates farthest from the sprue. Careful design, including reduction of runner size after each gate, can be used to obtain uniform flow through all gates but some trial and error is still usually necessary in arriving at proper gating ratios. The Sprue-Runner-Gate area ratio is settled to the pressurized system for zinc is kept at 1:2:1. If more than one ingate is used the rations pertain to the total area of all the ingates. Means the area of the each ingate equals to the single ingate area ratio.

For the simulation of the casting processes initial mold casting system was designed in accordance with the JICA standards [30]. It was assumed that the complete cast product is in the drag (or cope) of the mold. The filling time was calculated and found to be 5 seconds according to H.W. Dieterts (JICA, 1995): $T = S\sqrt{W}$. Where S is a coefficient depends on the thickness of the casting, and W is the total pouring material weight.

In multiple gating systems it has been found that often most of the feeding is accomplished by the ingate farthest from the sprue. This is the due to improper proportioning of the cross sectional area of runner and ingates. Because of the frictional losses and the abrupt change in cross sectional area these points, the liquid metal has relatively low velocity and fairly high pressure. Hence it will readily flow into the farthest gate. The gates nearer the sprue will have less metal flowing through them because of higher velocities and lower pressures. To avoid this adequate sprue-runner-gate ratio is developed to maintain a more uniform distribution of the metal in the feeding system and hence more constant velocity and pressure conditions. To be completely satisfactory, however the runner beyond each gate should be reduced in cross section to balance the flow in all parts of the system and thereby to equalize further the velocity and pressure. Furthermore, the design is streamlined to avoid sudden changes in direction that might create turbulence. Runner and gates are designed to obtain the following characteristics:

1. Absence of sharp corners or changes of section that may lead to turbulence.

2. Proper relation between cross-sectional areas of gates, runners and sprue.

3. Proper location of gates to ensure adequate feeding of metal into mold cavity.

Gates are channels through which molten metal flows to fill a mold cavity. To produce sound casting, gates must also be designed to completely fill the mold cavity (prevents “misruns”) and to promote feeding (establish proper temperature gradients). In addition to this choke are to be placed with gates or before sprue well in order to reduce the turbulence of the metal flow. To fill thin sections completely, flow rates must be high, but not so high as to cause damaging turbulence. Multiple gates are frequently used, with individual gates extending to areas where a misrun is likely to occur. Adequate vents should be incorporated where a back pressure due to mold gases may otherwise occur and hinder metal flow. The gating system must be designed to promote the best possible temperature gradients. Gating and risering are closely interdependent processes. The purpose of gate is to feed the casting at a rate consistent with the rate of metal solidification, to control the solidification process and to provide the adequate fluid flow behavior. For computing the choke area of dumbbell specimens who are to be casted both partially in the cope and drag, the choke and Gate dimensions can be calculate by using the following relationship [34]:

$$Ac = number\ of\ gate * Ag \qquad \text{Eq. 3.13}$$

$$Vc = fr\sqrt{2gH} \qquad \text{Eq. 3.14}$$

$$Ac = \frac{1}{fr.t.\sqrt{2g}}\left[\frac{V_D}{\sqrt{H}} + 1.5(h)\frac{Vc}{\sqrt{H^3} - \sqrt{(H-h)^3}}\right] \qquad \text{Eq. 3.15}$$

Where, A_c denotes the Choke Area, V_D is the Drag volume, V_c is the Cope volume, *fr* denotes the frictional loss factor, *H* represents the Effective ferrostatic head in sprue, *t* is the time, *g* is the gravitational force and *h* denotes the Height of casting in cope.

Designing of the downsprue and the sprue well was replicated from the previous research works and as per standards defined by JICA [30]. But during designing of the sprue it has been taken into consideration that the cross-sectional area of the downsprue bottom must be around five times that of the sprue exit to the runner and the depth must be around double to that of the runner in order to absorb enough kinetic energy of pouring metal to avoid turbulence in the flow.

Multi-gate system and double gate system has been designed for the dumbbell specimen and impeller part respectively. As shown in figure 3 below, this resulted in the following calculations for the Total choke area Dumbbell.

$$A_c = \sum A_{1\text{-}16} \qquad \text{Eq. 3.16}$$

Where, A_c denotes the Choke Area, $\sum A_{1\text{-}16}$ is the sum of total areas of all the 16 in-gates for the dumbbell specimens casting mold design.

The area of the Runner should be at least 3 to 4 times that of the ingates or choke area according to the number of ingates, so the runner area A_r can be calculated for the dumbbell, according to the choke cross sectional area A_c as: $4A_c = A_r$. Also it can be written as: $a = \sqrt{A_R}/2$. Where, a represents the length of side length of cross sectional area of gate runner and A_R denotes the cross sectional area of runner, which is found to be 0.95 cm for the dumbbell specimen.

Risering is a technique to produce an additional component in the gating system with the casting in order to avoid shrinkage porosity in the casting after solidification of molten metal. Proper design of risering system depends upon the freezing pattern of the alloy and the freezing time of the riser relative to the casting.

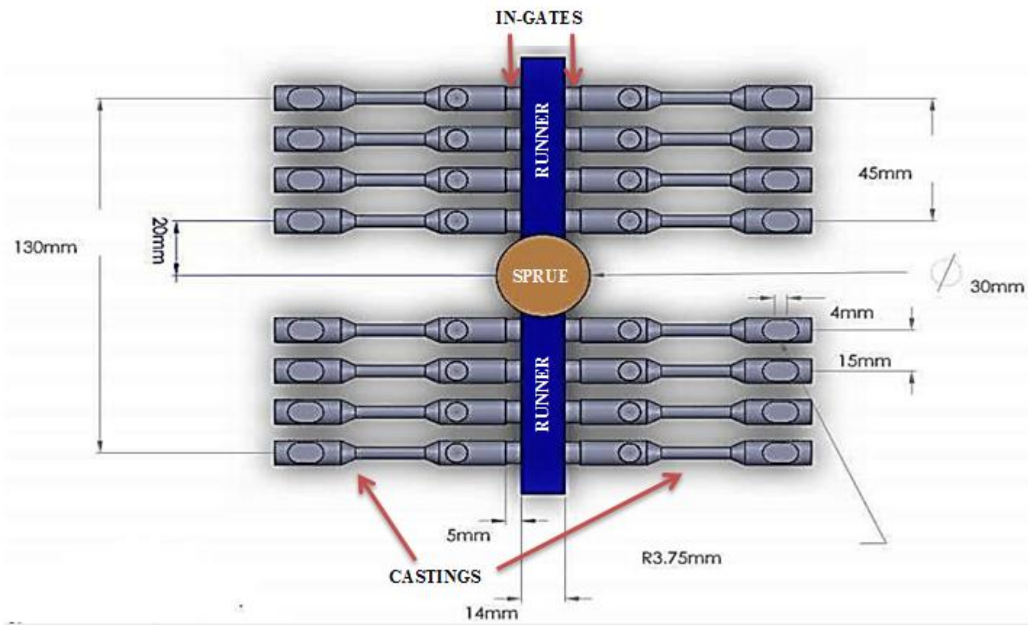


Figure 3 Schematic Casting System for Dumbbell

The primary function of riser is to feed metal to the casting as it solidifies. The riser requirements depend considerably on the type of metal being poured. If the riser will not be added then the some region in the casting will get the porosity due to shrinkage in that region resulting from the directional solidification that develops there due greater heat extraction from those region compared to other. If the casting have variety of section thicknesses then various risers are to be placed in order to get overall sound casting.

Table 4 Summary of Casting System Dimensions for Dumbbell – units in cm

A_C	$A_1 = A_2$	a_r	H	h	A_S	A_T	A_B
2.94	1.47	0.61	8.0	2.0	5.89	5.89	2.00

Non-ferrous alloys which have an extended solidification range require excessive and sometimes elaborate feeding systems to obtain sound castings [35]. The variation that can be expected in the volumetric shrinkage of some metals is shown in Table 3. As experienced in the case of zamak alloy in this study. The values shown in the Table 4 represents minimal requirements that must be satisfied by the riser.

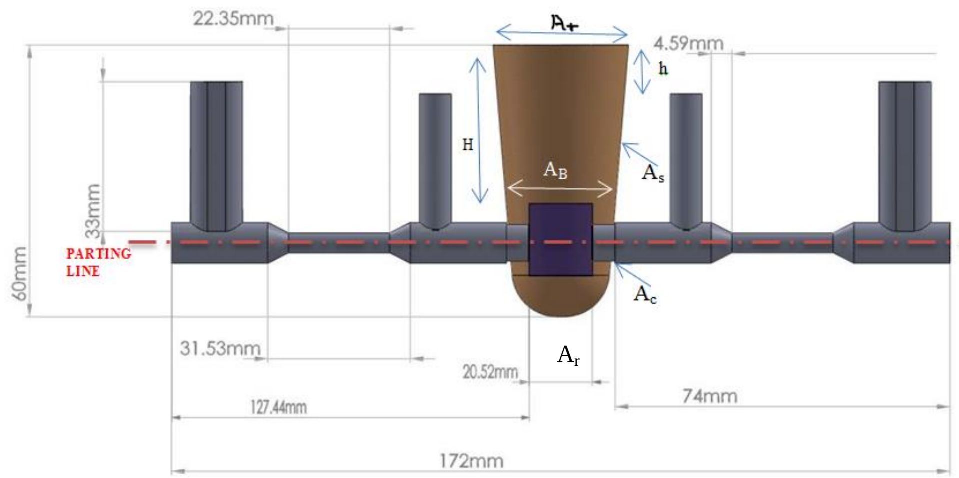


Figure 4 Mold Component Design for Dumbbell

There are two conditions to be fulfilled during riser designing for removal of shrinkage from the metal have a good quality casting.

(1) Riser Size: The size of the riser should be designed to have the ratio (volume/area)^2 greater than casting. Also the riser should be solidified after the casting so that it can feed the molten metal to the casting to avoid shrinkage formation.

(2) Riser Placement: In the castings made of alloys with higher centerline feeding resistances, the effective feeding distance of risers should be reduced as compared to other alloys.

Intelligent analysis of the solidification and thermal profile patterns is necessary in order to avoid the formation of shrinkage porosity in the casting. It is evident that to develop the best engineering properties in a given casting, the shrinkage voids must either be eliminated or isolated at a location of low stress. Shrinkage of some common metals and alloys are given in Table 3.

The riser and the casting it feeds should be considered an integral system because a casting cannot be made sound without adequate feed metal, no matter how much attention may be paid to other details. The problem of providing this feed metal during the entire solidification period of the casting involves quite a few variables of which the important ones are: riser shape, size and location, grouping of casting, riser connections to the casting, use of chills, use of insulators and exothermic compounds.

A casting loses its thermal energy by transferring it to its surroundings by radiation, conduction, and convection. The surface area of the casting relative to its volume is important in determining the rate of this heat transfer which can be expressed mathematically by Chvorinov's solidification time formula given in Eq. 3.4.

If the cylindrical casting is poured on end is to be fed by a riser, it is obvious that the riser must have a diameter at least as large as that of the cylinder. Various alternative procedures are available to calculate riser size. [36-38] one of these takes into account the shape factor of the casting, which is expressed as the sum of the length and width of the casting divided by the thickness (L + W / T).

Spherical shape is ideal for making the risers to have minimum deviation in the solidification rates of the riser and the castings. Spheres are impractical to mold so different feasible shapes are selected keeping in view in order to achieve smallest surface-area-volume ratio. Spherical risers are considered to be more efficient than square or rectangular risers; the ratio of surface area to volume is lower, and heat loss to the molding material would seemingly be less. Accordingly, the effective feeding life of round risers should be best, and foundrymen usually use round risers whenever possible. Spherical risers would have the lowest ratio of surface area to volume, but they would be impractical. Risers must be at least 15 to 20% larger in diameter than the section they are to feed (unless extensive chilling or insulation is employed). The riser height never needs to be greater than 1.5 times the diameter and can usually be less. Short, fat, top risers are more efficient than tall, slim ones of the same volume. The great value of Caine's curve [39] lies in the fact that it permits plotting data from a wide variety of casting and riser shapes and sizes on single set of co-ordinates.

Riser size is determined by two factors: Firstly, the freezing time of riser must exceed the solidification time of casting, at least to some extent, and 2. The riser must supply sufficient feed metal to compensate the liquid-solid shrinkage.

Riser size is calculated according to the risering curve after finding the shape factors involved as provided by Caine [40], using the following risering equation: $x=(a/y-b)+c$. Where, x represents the freezing ratio, y = riser volume/ casting volume, a is freezing characteristics constant, b is the liquid-solid solidification contraction, and c denotes the relative freezing rate of riser and casting.

Shrinkage allowance on patterns is a correction for the solidification shrinkage of the metal and its contraction during cooling to room temperature. The total contraction is volumetric, but the correction for it is usually expressed linearly. Pattern shrinkage allowance is the amount the pattern must be made larger than the casting to provide for total contraction. Pattern draft which is the taper allowed on vertical surfaces of the pattern to permit its withdrawal from the mold without tearing it. As a thumb rule 1/16 in or one degree taper in machined patterns is common among casters. Good pattern provides better gating practice for castings that require that the runner and gating system including risers and gates to be attached to the pattern.

3.3 Process Sequence of Molding Techniques

Castings techniques which have been utilized are discussed in detail with the work sequence in the form of process flow diagrams for each molding technique also been illustrated to have a clear view of the experimental methodology. Additional work steps have been added according to the simulations, included for the optimization of the casting processes to get sound casting.

3.3.1 Sand Mold Casting

The process which utilizes the mold made of silica or other type of sands for casting high temperature metals and alloys is called "Sand casting". Apparently all metals can be casted by this process keeping in view the limitations to some low melting alloys, low dimensional precision for small castings, poor surface quality and the defects arise during the operation. Figure 5 shows the Process Flow diagram of sand casting followed during experimentation. Process specified limitations of sand molding process include:

- Moisture in the sand mold causes hydrogen related defects in the castings.
- Improper Molding results in complete rejection of casting due to unsoundness.
- Castings produced by sand molding may not have high dimensional tolerances and surface finish as achieved by investment casting and die casting processes.
- The surface finish and dimensional accuracy of ± 0.016 inch in smaller castings is observed.

Sand and clay are normally used due to their high melting temperatures and resistance to degradation by air at high temperatures heating. Sand mixed with the clay should provide enough porosity to provide space for the evolution of the gases during casting operation. There must enough refractoriness in the mold materials to with stand high melting temperatures of the molten metals and must have enough strength to hold the shape of the mold.

Unconventional considerations are involved to cast non-ferrous metals and alloys through sand mold casting technique. Recommended molding sand for the non-ferrous castings is of a selected fine grain to ensure smooth surface of castings as high refractoriness is not required since most non-ferrous metals and alloys have melting temperatures lower than those of ferrous metals and alloys. As for the selection of the type of mold in which a piece is to be cast, there are no hard and fast rules. Only the points to be considered are lowest possible cost, quality of casting, production time, equipment availability and the thermal conductivity of mold material as in Table 5.

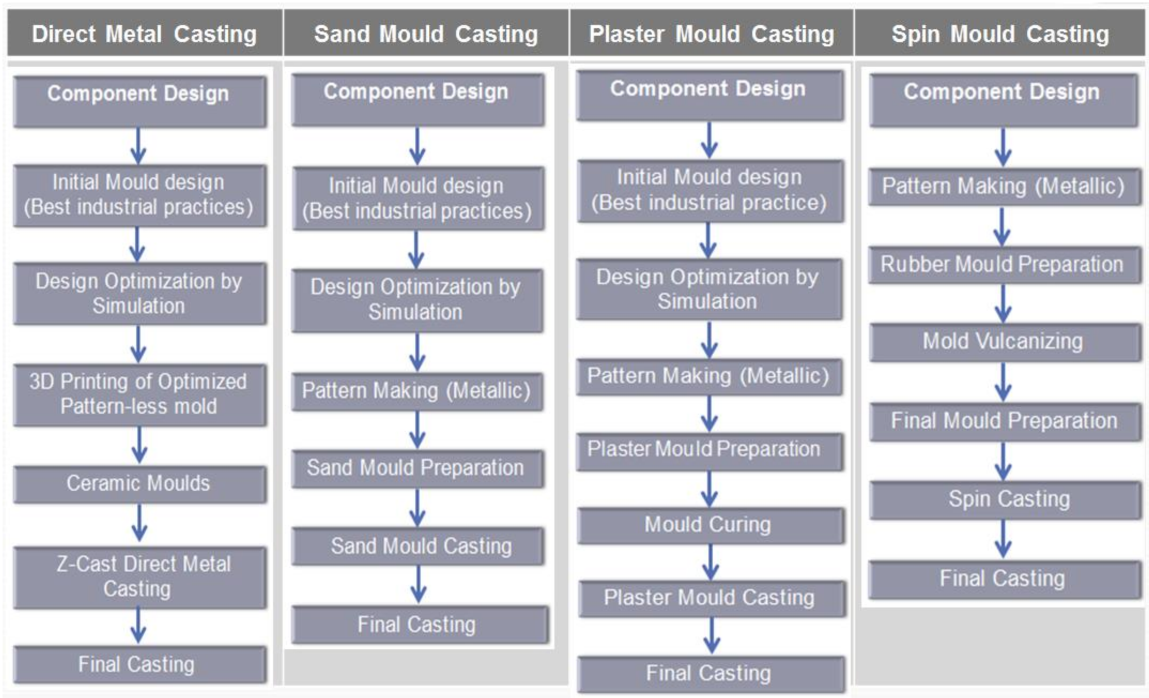


Figure 5 PFD of Gravity Casting methods

3.3.2 Plaster Mold Casting

The use of plaster as an investment material for casting numerous articles and parts has grown considerably because of the ability of plasters to dry quickly. Casting in plaster molds has become a useful casting process. [41][42]. The application of Plaster of Paris (gypsum or $CaSO_4$. nH_2O) molds is limited to non-ferrous alloys (silver, gold, aluminum, magnesium, copper, and alloys of these metals, particularly brass and bronze, etc.) whose melting temperatures do not exceed 2000^{o}F (1100^{o}C), since the molding materials cannot sustain high temperatures. Small to medium sized brass, bronze, and aluminum castings used in the automotive and aircraft industries are successfully casted by the plaster mold casting process. These castings offer dimensional accuracy and surface finish of such excellence that machining time is considerably reduced. Among the numerous small parts cast by this process are gears, housings, pump parts, cams, levers, ball races, hard ware and plumbing fixtures.

The plaster molding process consists of forming a plaster mold around a properly finished metal pattern. The plaster of Paris consist of gypsum is mixed with water to get a consistency of 140 – 180. Consistency is the amount of water in pound added per 100 pound of plaster. As a general practice and thumb rule 100 parts of a plaster mixture is mixed with 160 parts of water and stirred slowly to form uniform slurry; and it is recommended to add the plaster into the water rather than adding water to the plaster to form slurry. The mixing time and pattern is to be judged by hit and trial method as frequent and quick mixing pattern may entrap the air in the slurry with increased mold permeability and reduced strength; while very slow mixing may set the plaster earlier.

The slurry is poured over a carefully made matchplate-type pattern, usually of metal; in a few minutes at room temperature the mixture develops an initial set, and the pattern can be removed. Metallic pattern is required as the plaster contains water which swells-up the wood patterns and making them impossible to withdraw. The mold is made in two sections to facilitate withdrawal of the pattern. It is cured after the pattern is withdrawn and made ready to receive the molten metal. The patterns are removed after the plaster setting of about 20–30 minutes. Figure 5 shows the Process Flow diagram of Plaster Mold casting followed during experimentation. The setting process of plaster is accelerated by the hydration of gypsum by following reaction:

$$CaSO_4 + \frac{1}{2}H_2O + \frac{3}{4}H_2O \rightarrow CaSO_4 + 2H_2O + Heat \qquad \text{Eq. 3.27}$$

After the setting of plaster, mold is baked in oven at 200-425°C in order to remove all the moisture from the plaster mold otherwise hydrogen related defects occurred in the final casting. The baked mold is hard and brittle requires careful handling and assembling. Dimensions can be held to an accuracy of about 0.008 to 0.01 in. per in., and casting surfaces are excellent, often requiring neither machining nor grinding.

Plaster mixes suitable for the production of good quality castings have been developed in recent years, most of them consisting of proper proportions of gypsum and water, to which plastic materials and certain other ingredients are added. Plaster consists of proportions of gypsum powder, $CaSO_4$. ½ H_2O and other contents including talc, asbestos fiber, silica powder, and others, to control the shrinkage of the mold and setting time, with the ordinarily contents of 20% to 30% talc to prevent mold cracking, and may contain compounds such as magnesium oxide to hasten setting time, or other compounds to retard setting time.

Materials such as lime or cement can be added to control expansion of the plaster during baking. Chemical changes in the mixing and baking, however, involve only the water of crystallization of the gypsum. As received, calcined gypsum is $CaSO_4$. ½ H_2O; during the initial set, it reacts with the water of the slurry to form $CaSO_4$. $2H_2O$. when dried at temperatures below about 160°C, it reverts to $CaSO_4$. ½ H_2O, and, at temperatures above 160°C, the last combined water is driven-off, leaving anhydrous calcium sulfate ($CaSO_4$). Because molds of metal casting plaster possess very low permeability, care must be taken to remove all combined water, and avoid absorption of moisture after baking.

The main features of plaster casting process includes casting of low to medium melting metals and alloys having thin section with close dimensional tolerances and good surface finishes. Also this process can accommodate the insertion of chills in the molds and permeability of molds is additional advantage of plaster casting. But this process has the limitation that due to decomposition of sulfur present in the gypsum at high temperatures plaster casting is limited to only non-ferrous low melting metals and alloys. Another good reason for this technique is that the smoothness of plaster makes it possible to produce castings which offer fine surface finish and dimensional accuracy. Plaster investment molds are not permanent and are destroyed during the castings are removed from the mold.

3.3.3 Ceramic Mold Casting using 3D Print Pattern-less Z-Cast Technique

3D Printing is a subclass of rapid prototyping, used as modern technique to get 3D objects directly and quickly from 3D-Modelling software. This technique was appeared in the mid-90s and now these 3D printers seem to be dream machines for design engineers and artists, for making prototypes of their products for development and marketing purposes.

The 3D printing is much faster in job operation then other rapid prototyping techniques. As they can print the similar jobs within hours and minutes which the other rapid prototyping machines do in days and weeks. [43]

These are termed as "3D printers" because most of the machines which are categorized as 3D printers utilize the inkjet printing technology in printing the 3D model by spraying the resin on printing stage through inkjet nozzles. Also FDM (Fused deposition modeling) and Ultraviolet Curing Process are also followed by some other printing machines.

Using the 3D printing technology to print ceramic mold diminishes the need of troublesome and time consuming pattern making step for casting of metals. This technology of casting using the 3D Printed Mold directly from CAD model with pattern-less assembly is called “Direct Metal Casting”. The 3D CAD files in ZBD or STL (stereo lithograph) format are required to get the job done using the 3D printer. These files of casting system and mold can be modeled with popular commercial programs like Rhino3D, AutoCAD, or Solid Works. After input the source 3D CAD file, the 3D printer “prints” the 3D model of the mold on printing platform using printing powder usually plaster and ceramics with other additives by spraying the suitable binding agents. Wherever the binding agent touches the powder bed, the ceramic powder get stiffens, and a solid ceramic layer of the digital model is formed. [43]

In the same manner the printer adds the layers over layers of plaster ceramic powder to complete the 3D Pattern-less mold. Finally, the mold is baked to remove moisture or unused binder then; metal upto 1200^{o}C can easily be casted in this ceramic mold. The whole manufacturing method has been illustrated by the process flow diagram in Fig. 5.

Table 5 Thermal Conductivity Values for Mold Materials

Mold Material	Thermal Conductivity (W/m°K)
Sand Mold	0.8 - 1.2
Plaster Mold	0.18 – 0.22
Ceramic Mold	22 – 30
Silicon Rubber Mold	0.2

CHAPTER 4

OPTIMIZATION OF THE MOLD DESIGN USING NUMERICAL SIMULATION TOOL

Current chapter enlightens the computer simulation tool (MAGMASOFT® 5.2 (MAGMA^5)) utilized for the casting process simulation based on numerical models and mathematical relationships. Brief introduction of the software tool has been given in the first section. While the preceding sections involve simulation methodology and working sequence in the second section. Detailed procedure for casting simulation to get optimized mold has been discussed in the third section including the simulation results for different casting designs. This chapter has been designed to accomplish our task 2 for demonstrating the feasibility of Advanced Simulation Techniques in refining a traditionally designed mold towards an improved and near perfect mold and sound quality cast product by optimizing the casting system design and process parameters using an example of a 3D printed ceramic molds casting process in minimizing the casting defects.

4.1 Introduction to the Numerical Simulation Tool

In this modern era of inventions and discoveries, market competition is getting tough day by day. To be competitive in the market and to do profitable business it is necessary to develop and adopt advanced industrial tools and strategies which facilitate the product design and manufacturing, cost effectively. Keeping in view of the day to day variations in the customer demands and market applications, continuous development of new and improvement of prior products is vital. This requires quick and reliable solutions that help reducing the overall product lead time, production cost and quality efficiently. Over the last few decades, casting simulation softwares and rapid prototyping technology have gained popularity among the scientists [9] and the manufacturers globally. Just after their emergence in the market these technologies have been adopted industrially providing promising results in improving the product quality and manufacturing capacity meeting high customer demands with reduced lead time [10, 11].

MAGMASOFT® 5.2 is a tool for fast and efficient examination of the filling and solidification processes. The most important features of using this tool are the cost reduction and reliable quality production. It uses the method of numerical calculation to simulate the entire casting process from the filling of the melt into the mold up to the solidification and subsequent feeding in the form of physical model. It provides the computer based on-screen "cold casting" facility which allows to improve the casting system design step by step.

MAGMASOFT® 5.2 (MAGMA[5]), software is embedded with several mathematical relationships and numerical models, with different boundary conditions to simulate the metal filling and solidification patterns, thermal and mechanical properties both in molten and solidified form.

The flow of the molten metal inside the mold is governed by the flow velocity which is linked with the static pressure head and the area of the gates. For calculating the fluid flow Bernoulli's Theorem is utilized by the MAGMA[5] [63]:

$$p_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = p_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + \Delta p_{loss,1-2} \quad (4.1)$$

Or

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = const. \quad (4.2)$$

Where p is static pressure, ρ is density, v is velocity, g is gravitational acceleration and *h*. is height w.r.t reference point. Bernoulli's Theorem is used for the conservation of the energy in fluid mechanics. Furthermore, the Pressure-head loss during the melt flow the software implements Darcy-Weisbach equation [63]:

$$\Delta p_{loss} = f \frac{L_{1-2}}{d} \frac{\rho v^2}{2} \quad (4.2)$$

L_{1-2} is the gate dimensions, *d* is diameter and *f* denotes the coefficient of friction. Assuming mass supported over static volume of molten metal flow, MAGMA[5] utilizes Eulerian relationship to predict the relation of mass conservation [63]:

$$\frac{\Delta m}{\Delta t} = \sum_i \dot{m}_i \quad (4.3)$$

Continuity behavior for the molten metal flow using the mass conservation equation is adopted by the simulation tool as mentioned below [63]:

$$\frac{\partial u_1}{\partial x_1}+\frac{\partial u_2}{\partial x_2}+\frac{\partial u_3}{\partial x_3}=0 \tag{4.4}$$

Considering the molten metal as the Newtonian fluids, MAGMA[5] utilizes the Stokes hypothesis [63], for finding the normal and shear components of the viscous stress tensor using the relationship:

$$\tau_{11}=-\mu\left[2\frac{\partial u_1}{\partial x_1}-\frac{2}{3}\left(\frac{\partial u_1}{\partial x_1}+\frac{\partial u_2}{\partial x_2}+\frac{\partial u_3}{\partial x_3}\right)\right]=-\mu\left[2\frac{\partial u_1}{\partial x_1}-\frac{2}{3}divu\right] \tag{4.5}$$

In above equation div_u denotes divergence operator of the velocity vector. Hence, viscous stress tensor (τ), of the Newtonian fluid becomes [63]:

$$\tau=\begin{bmatrix}\tau_{11} & \tau_{12} & \tau_{13}\\ \tau_{21} & \tau_{22} & \tau_{23}\\ \tau_{31} & \tau_{32} & \tau_{33}\end{bmatrix}=\begin{bmatrix}-\mu\left(2\frac{\partial u_1}{\partial x_1}-\frac{2}{3}divu\right) & -\mu\left(2\frac{\partial u_1}{\partial x_2}+\frac{\partial u_2}{\partial x_1}\right) & -\mu\left(2\frac{\partial u_1}{\partial x_3}+\frac{\partial u_3}{\partial x_1}\right)\\ -\mu\left(2\frac{\partial u_2}{\partial x_1}+\frac{\partial u_1}{\partial x_2}\right) & -\mu\left(2\frac{\partial u_2}{\partial x_2}-\frac{2}{3}divu\right) & -\mu\left(2\frac{\partial u_2}{\partial x_3}+\frac{\partial u_3}{\partial x_2}\right)\\ -\mu\left(\frac{\partial u_3}{\partial x_1}+\frac{\partial u_1}{\partial x_3}\right) & -\mu\left(\frac{\partial u_3}{\partial x_2}+\frac{\partial u_2}{\partial x_3}\right) & -\mu\left(2\frac{\partial u_3}{\partial x_3}-\frac{2}{3}divu\right)\end{bmatrix} \tag{4.6}$$

Several other mathematical models for predicting the thermal and stress analysis are there on which the MAGMA[5] simulation is based upon which is not possible to mention here due to space constraints.

4.2 Simulation Sequence in MAGMASOFT®

MAGMASOFT®, software is a complete system involves all the required functions from casting geometry (casting system, final product, cores, sprue, runner and riser location and design, etc.) and the casting parameters (pouring temperature, time, pressure, filling velocity, etc.) to the final solidification and final post treatments of the casting product. The process flow sequence of MAGMA[5] involves the project administration option in order to save different casting simulations data inside. Second is the preprocessing, which involves the geometry importation and modification, and material specification database input options. Third is the enmeshment, which involves the meshing and division of geometry into several numbers of elements for performing Finite Elemental Analysis (FEA). Next is the simulation step, then final is the Post processing function which involves the representation and management of simulated results. Figure 6 illustrates the working sequence of the MAGMA[5] simulation:

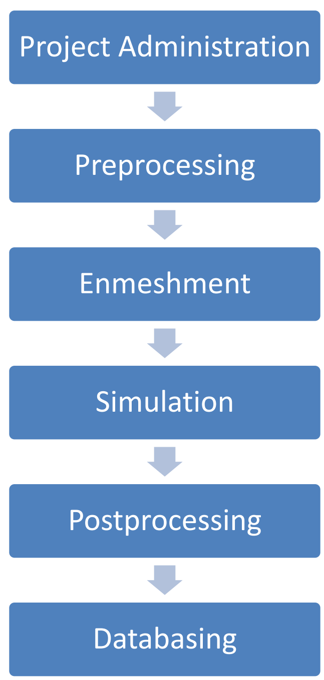


Figure 6 Working methodology of Simulation software

4.2.1 Geometry Modeling (Preprocessing)

Simulation of the filling and solidification process requires the geometry of the casting process is available in 3D CAD files via general .STL interface. MAGMA[5] has an integrated geometry modeling, through which it is easy to model the casting system quickly and reliably for testing the suitability of the existing geometry with the final product quality. A wide range of modeling functions allows creating complex casting geometries. Furthermore, the CAD geometry from other softwares can easily be imported to the geometry interface. After importation the CAD files can be modified in this interface subsequently, with the help of CAD module. Figure 7 shows the imported CAD files of casting system in the MAGMA[5] geometry interface.

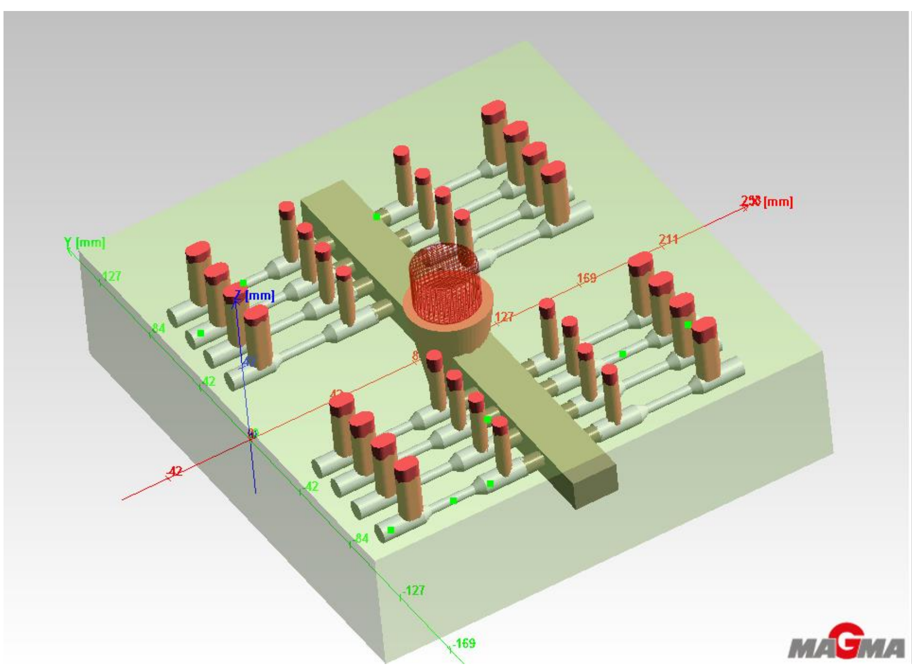


Figure 7 Casting System CAD model in MAGMA[5] geometry Interface

Furthermore, the control points were defined at several locations of the ingates, risers, runners and casting in order to find out the certain simulation results like finding cooling curves, thermocouples, tracer particles and active feeding controls at specific locations. Figure 8 illustrates the distribution of the control points at different locations of the casting system. The coordinates of the control points has been summarized in Table 6.

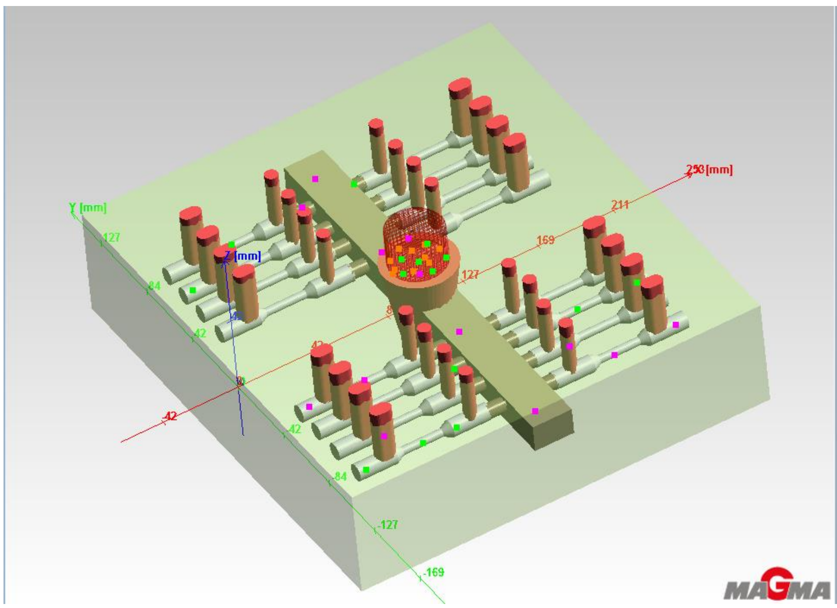


Figure 8 Control Points defined in Casting System within MAGMA[5] Interface

Table 6 Coordinates of the control points for thermocouple readings

Thermocouple Code	X	Y	Z
Th_Run3	95.95	-115.37	22.38
Th_Run4	95.47	-50.68	21.31
Th_CstCnt2 (nr pour)	38.5	-54.79	22.32
Th_CstCor1	6.41	-55.57	22.3
Th_Rsr1	18.9	-108.89	39.27
Th_RsrR2	123.04	-108.6	47.13
Th_CstCnt1	148.15	-108.9	22.47
Th_CstCor2	180.25	-108.79	21.98
Th_Pour	87.2	-27.24	37.56
Th_Run2	95.4	79.4	19.74
Th_Gat1	80.32	68.18	20.15
Th_Gat2 (nr pour)	110.19	18.64	19.59
Th_Run1	93.04	15.15	20.98

4.2.2 Material Definition, Boundary Conditions and Feeding Characteristics

After performing the geometry settings, the process parameters, material definitions, the boundary conditions and the feeding characteristics are to be input as a part of the preprocessing. The material definition includes the metallic alloy to be cast with its important mechanical, physical, chemical and thermal properties, second is the material input for the mold to be utilized. The material selected for the casting was according to available Zn alloy (ZAMAK) - the closest in chemical composition of the TEKALOY ZA-1 and for the mold materials for simulation of different processes includes the three types of materials including the Furan Sand, Al_2O_3/ZrO_2, and the $CaSO_4.2H_2O$ (Plaster) with the properties already found in the software database.

Second the boundary conditions are to be defined as the preprocessing parameters input for the simulation calculations. The boundary conditions for the simulations to run were:

Table 7 Boundary Conditions for the FEM Analysis

Stop solidification: as cast temperature reaches 381^{o}C.
Pressure: 1 atmosphere
Feeding characteristics: Normal feeding (Non-active feeding)
Initial molten metal Temperature: 500 ^{o}C
Initial mold temperature: 25 ^{o}C
Pouring Time: 8 Seconds
Percent Filling: 0% to 100% at every 5 % interval
Percent Solidification: 0% to 100% at every 5 % interval.

4.2.3 Mesh Generation for VOF Finite Elemental Analysis

MAGMA[5] includes the function of automatic enmeshment which provides rapid, accurate and flexible operation. Mesh generation is based on the number of elements input to the level of desired accuracy in the results. The scan sensitivity was set to 3,000,000 elements in this study in order to get more precise results. Second wall thickness is to be selected according to the geometry provided; alternatively the software will generate automatic wall thickness equals to 2-3 mesh elements. Mesh quality mapping provides the overall performance indications during the meshing and provides information about presence of anomalies found in meshes. Figure 9 illustrates the mesh quality of the final casting design simulated.

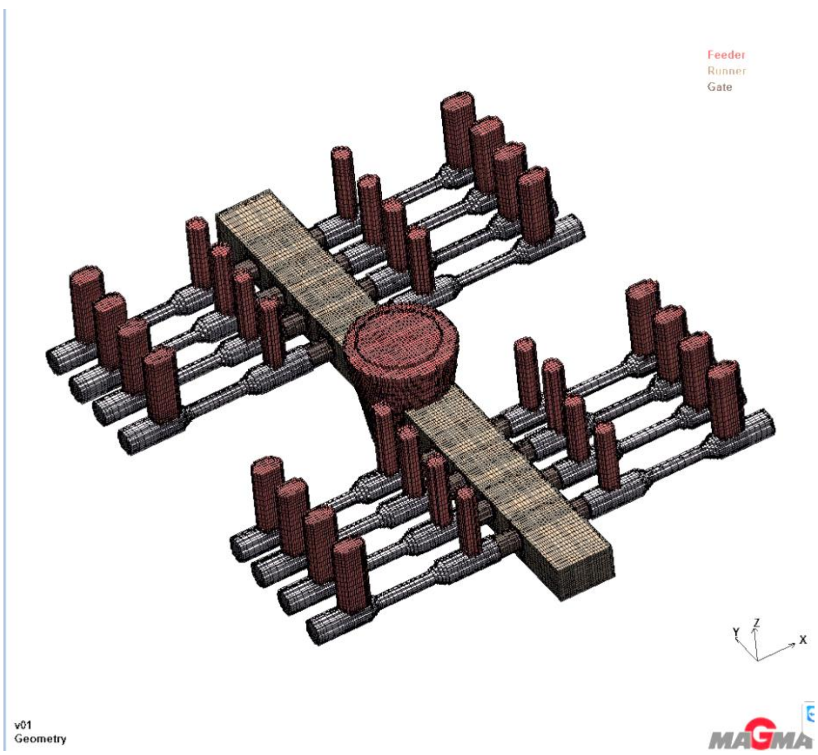


Figure 9 Geometry mesh quality of the casting system using solver5

There is an option in new version MAGMA[5] known as “Solver 5” which provides more clarified results, if the “Mesh for Solver 5” function is active, all elements that belong to the melt material class (cast, gate, etc.) and for which a material ID has not yet been clearly assigned, are examined again. In this process, the respective fractions of casting and mold within a single cell are determined and stored as additional information. In this way, geometries that have not been mapped ideally by meshing are considered more precisely in the simulation Figure 10.

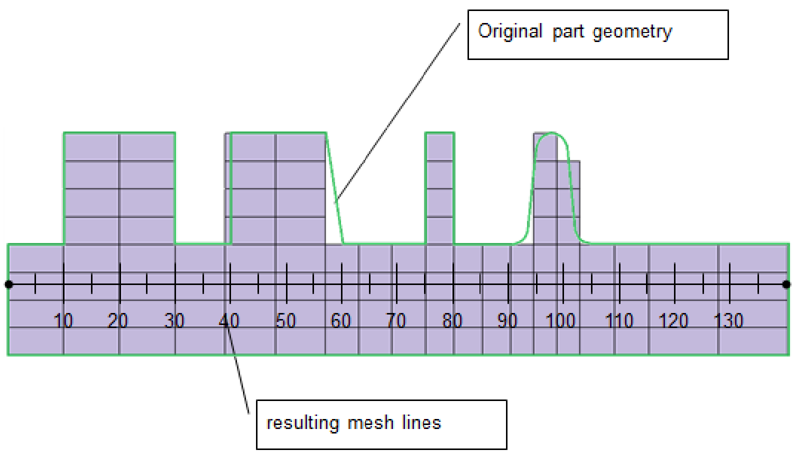


Figure 10 Geometry mesh filtration using solver 5 feature in MAGMA[5]

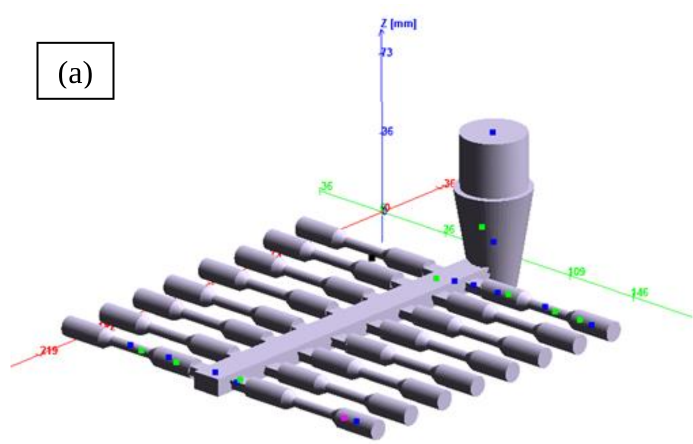
4.3 Mold Design Optimization by Iterative Simulations

Optimization of the casting process using simulation software involves a sequence of simulations in successions done to find out the best possible combination of casting parameters offered to the optimized design of runner and gating system [15, 13] with adequate geometry to get a sound casting without defects. The experimental methodology involves the steps of first designing of mold by applying standard industrial practices

[13]. CAD software has been utilized for 3D modeling of the part and mold as shown in Figure 8. Calculated mold design was then simulated by MAGMASOFT® in successions in order to get optimum design factors and casting parameters for further design modifications to optimize the flow, filling and solidification behavior, metal velocity, pressure, and temperature at runner gates and part.

Getting optimized mold design involves the proper placement and geometry of the casting system, tested for suitability with the help of simulations. Iterative simulations process has been adopted in order to find out the optimized casting system through simulation. Different design modifications according to the simulation results were assessed to get the sound quality castings with the thin sections-not possible to achieve by conventional gravity casting methods. Figure 11 (a, b, c) represents the sequence of designs modifications done to get the desired quality of casting, free from defects with the sequence simulation design #1 (11a), simulation design #2 (11b), and simulation design #3 (11c). In the first simulation the casting system was designed according to the industrial best practices with square in-gates, but after simulation some casting defects were found in the product.

(a)



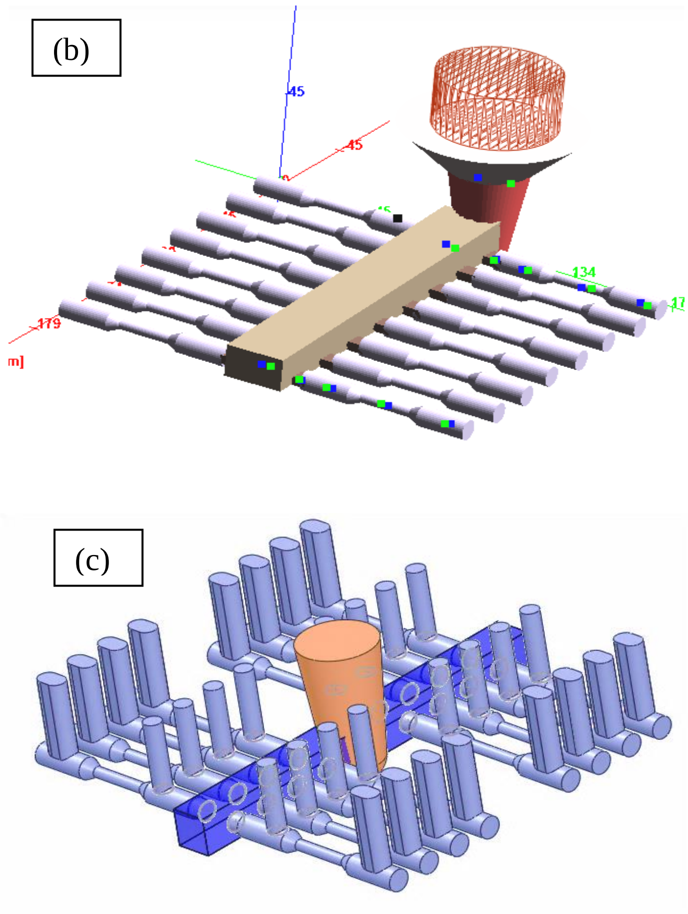


Figure 11 Sequence of designs modifications: Simulation design #1 (a), Simulation design #2 (b), Simulation design #3 (c).

Secondly, the casting system design was modified with the introduction of a pouring cup and in-gate design from square cross-sectional area to the round cross-section which further improves the casting quality in terms of better filling of metal in the constricted areas in the casting. Finally the design was more modified by the introduction of the central pouring mechanism (ensures uniform filling of the mold cavities on both sides) with the risers above the areas affected by the hot spot formations by improper flow and shrinkage at the certain regions found by previous simulations. The final modification was found fruitful in diminishing the effect of shrinkage by proper flow of molten metal and introduction of risers provided the excess metal to cover up the metal shortage in the region during solidification. This process of iterations have been optimized in the newer version of MAGMA with version 5.3 in which simultaneous simulations with all possible iterations can be run at the same time, saving simulation timings in the designing phase of the casting system.

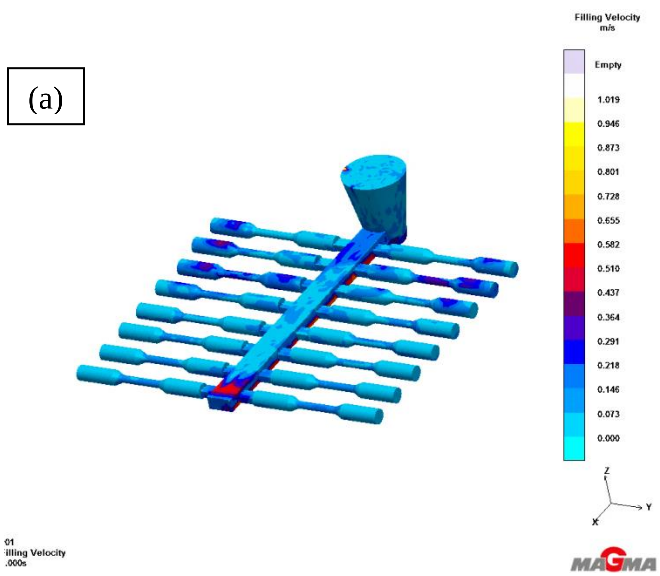
4.3.1 Filling and Solidification Behavior

Casting Simulation through the MAGMA[5] provides comprehensive process filling and solidification data with the casting materials properties. Simulation has been done with the built-in database of MAGMA[5]. It provides useful interpretations of the results in terms of material properties including, heat transfer parameters, metal viscosity, and casting density, filling and solidification patterns and defects analysis.

The filling behavior of the mold was simulated based on the key indicator: the flow velocity of molten metal inside mold through channels, pressure and temperature distribution in the casting system. The detailed analysis results have been discussed in upcoming sections. While casting soundness, porosity content and the hotspot formations were the key indicators for the solidification behavior analyzed during the simulations.

4.3.2 Flow Rate, Pressure and Thermal Behavior

After post processing of the simulation the following results have been obtained for the simulations. The flow velocity in the first simulation design was found to be irregular and variable across some parts of the casting system Figure 12 (a), while for the second design the it was found that some of the castings are empty and the velocity of molten metal is so disturbed that it is not reached at the corners of the dumbbell shape castings Figure 12 (b). The filling velocity has been optimized and is found to be smooth and the thinnest area in between the two thicker areas shows the higher velocities which ensures the good filling of the constricted corner areas of the casting Figure 12 (c).



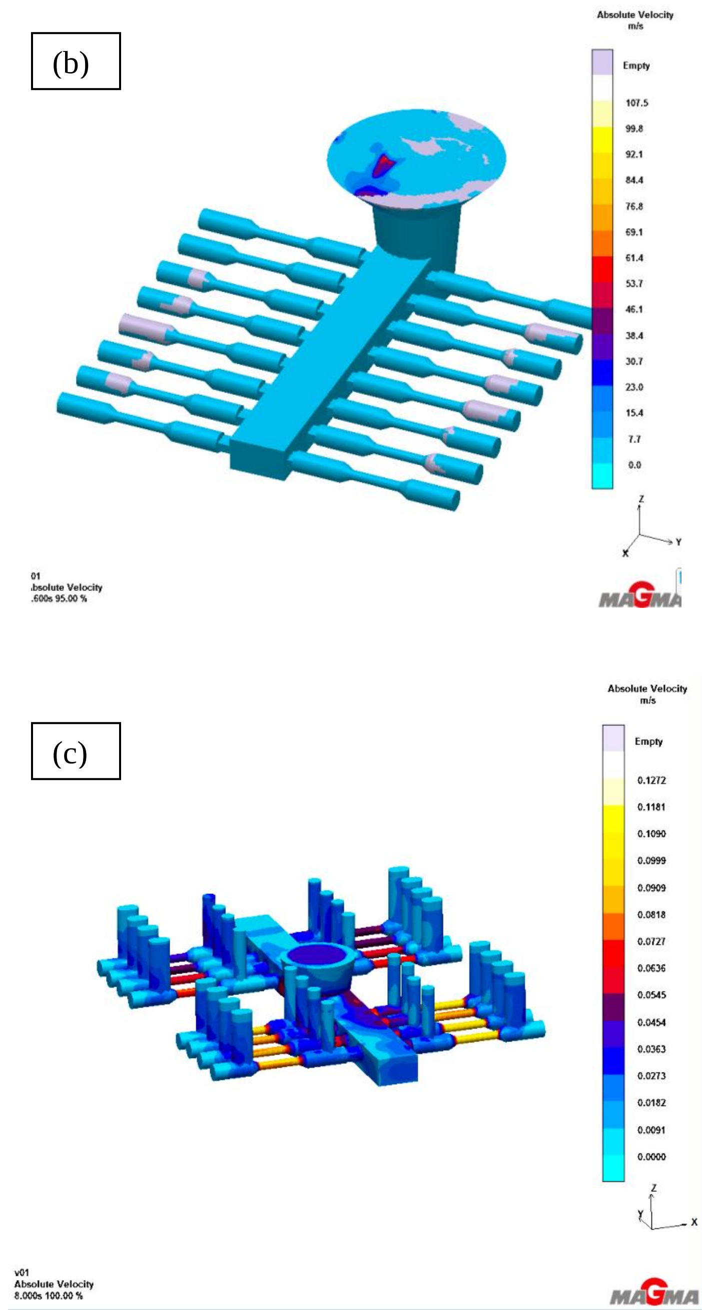
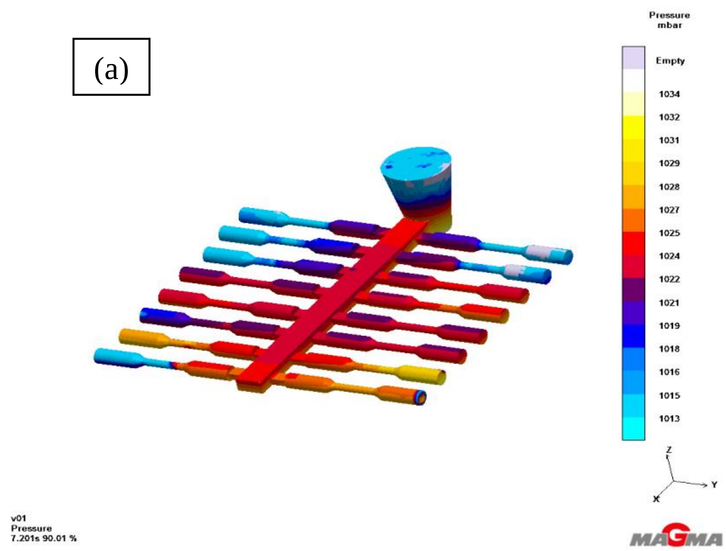
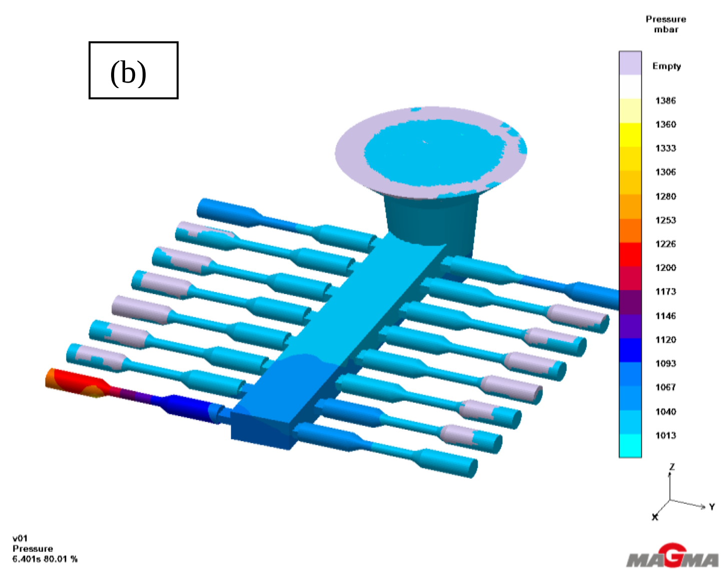


Figure 12 Molten metal flow velocity trends for different design modifications: Simulation design #1 (a), Simulation design #2 (b), Simulation design #3 (c).

Flow pressure trend in the first simulation design was found to be irregular and variable across the casting system Figure 13 (a), while for the second design the it was found that some of the castings are empty and some are already solidified during pouring without completely filled at the corners of the dumbbell shape castings Figure 13 (b). The pouring pressure has been optimized and the pressure trend across the casting system is regularized ensures smooth filling of the molten metal inside mold cavities without producing the turbulence in the flow Figure 13 (c).





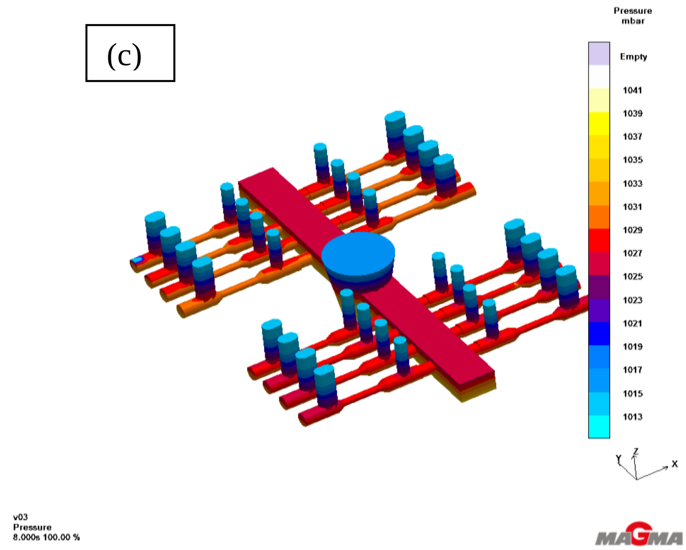


Figure 13 Molten metal flow pressure trends for different design modifications: Simulation design #1 (a), Simulation design #2 (b), Simulation design #3 (c).

As for the thermal behavior of the casting, temperature distribution trend across the casting system has been analyzed. In the first simulation design it was found that the solidification temperature distribution throughout the casting system was irregular and variable across the casting system Figure 14 (a) which is favorable for the shrinkage to occur and hot spot formations, while for the second design the it was found that some castings get solidified before the complete filling of the mold cavities for other castings. The variability of the temperature profile was so high that it seems to be favorable for several casting defects to occur after the complete solidification of the casting Figure 14 (b). The solidification temperature has been optimized and the trend across the casting system is regularized ensures smooth filling and solidification of the molten metal inside mold cavities without formation of shrinkage defects and hotspots Figure 14 (c).

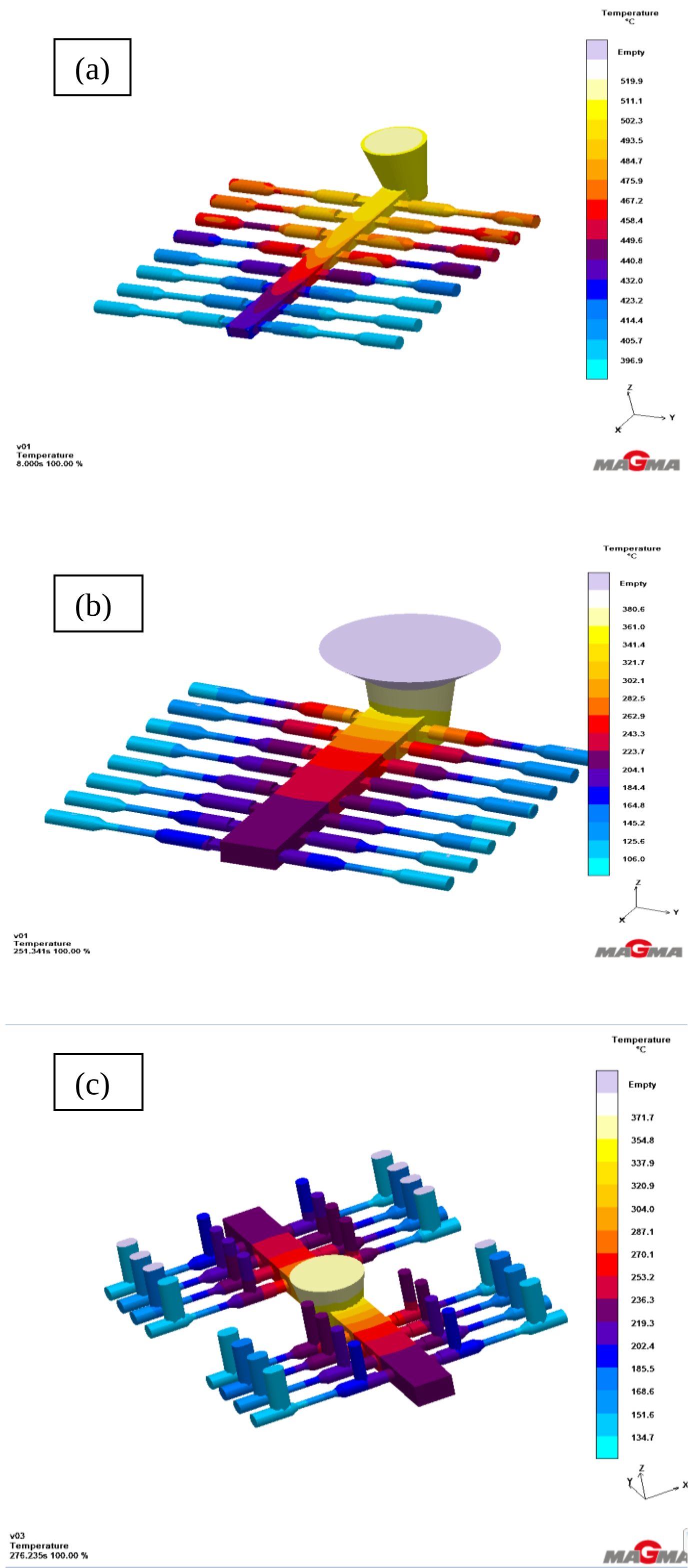


Figure 14 Molten metal flow temperature trends for different design modifications: Simulation design #1 (a), Simulation design #2 (b), Simulation design #3 (c).

4.3.3 Stress-Strain Behavior at Solidification

MAGMAstress module has been utilized for the calculations of the stress and distortion buildup in the solidification process. The simulation was based upon the temperature distribution that has been calculated time-dependently during the solidification simulation phase. Stress analysis helps to predict the residual stresses and distortions during the casting processes and the tendency of the formation of hot tear defects in the castings.

The following material's thermomechanical data was required by the software to simulate the stress behavior at solidification; this data is usually found in the software database:

- Young's Modulus
- Poisson's Ratio
- Thermal Expansion Coefficient
- Yield Stress
- Hardening Coefficient

The stress analysis for the tested design has been carried out to predict the stress distribution across the casting after solidification. Little amount of stress variation found among the three designs, design #1 and design # 3 Figure 15 (a and c) were found to be possess lower stresses after solidification while design # 2 resulted in relatively greater stresses along the castings Figure 15 (b).

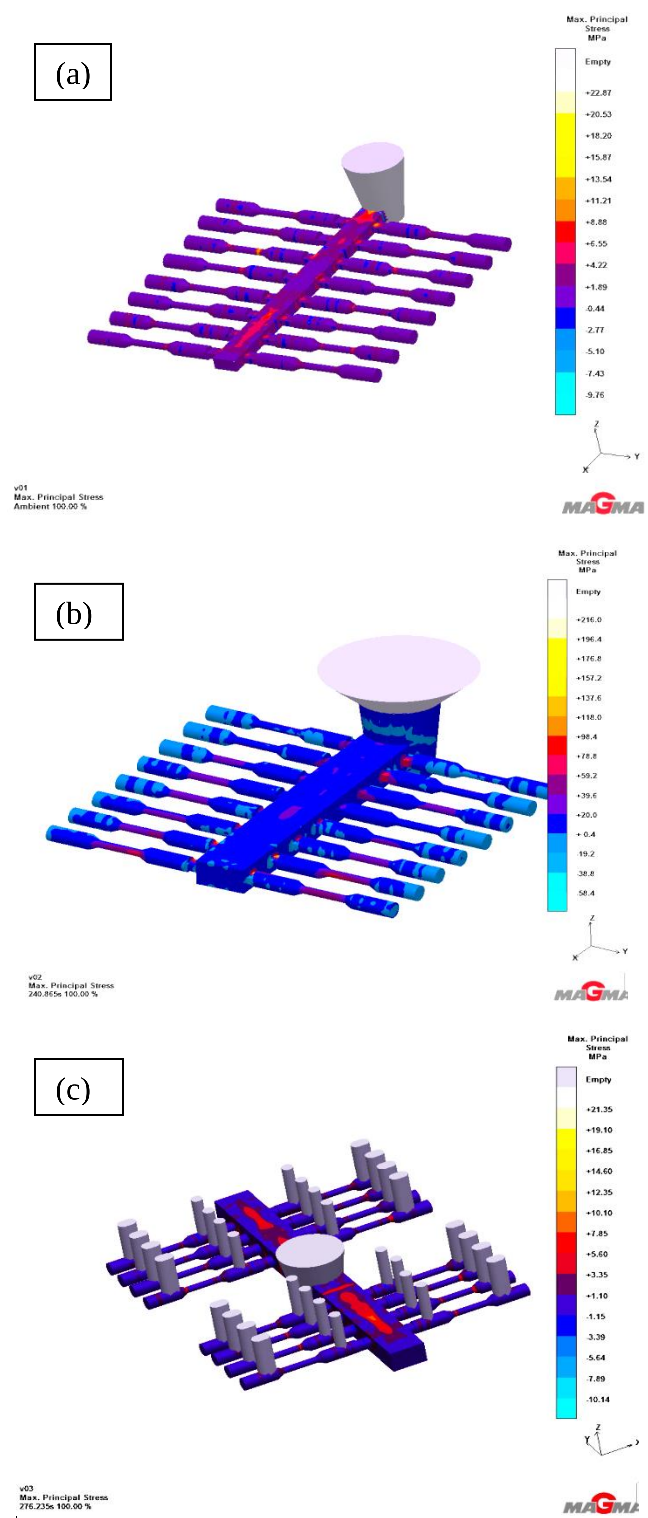


Figure 15 Principle solidification Stress distribution for different design modifications: Simulation design #1 (a), Simulation design #2 (b), Simulation design #3 (c).

CHAPTER 5

VALIDATION OF SIMULATED MOLD DESIGN BY REAL TIME CASTING

Optimized mold design with simulated casting process at optimal parameters has been validated by real time casting experiments, in order to analyze the conformation of real cast product quality with that of simulated in the casting software tool. In this section different types of casting processes that have been carried out for the validation of simulated results have been discussed with their practical implications. This chapter has been designed in order to fulfill the conditions to accomplish task 2 to see the feasibility Advanced Simulation Tools in getting sound quality casting using the example of 3D Z-Printing in producing the pattern less mold and to see feasibility of this process in reducing the time and cost of casting.

5.1 Mold Making for the Validation of Simulated Results and Comparative Assessment of Products of Gravity Casting Methods

Validation of the casting processes simulation by the method of real-time casting experiments has been adopted. The operating and process parameters have been replicated in the experiments to get the near-close results and product quality. As discussed before three types of gravity casting processes have been in consideration (i)

Plaster Mold Casting, (ii) Sand Mold Casting, and (iii) Pattern-less 3D Printed Mold Direct Metal Z-Casting. Simultaneously, the semi-centrifugal casting has also been carried out in order to compare the cast product quality from all the casting methods. Different aspects of molding and casting operations have been discussed in upcoming sections with detailed elaborations.

5.1.1 Plaster Mold Casting

Experimental methodology for the plaster mold casting involved the use of the two – piece split mold made by locally available "Plaster of Paris", commercially known as "gypsum powder". Slurry of the plaster was first made by mixing the contents with the plaster in a water approach as recommended in the literature. The proportion of mixing Figure 16a, for the plaster added to the water had the ratio 2:1 as a thumb rule. The molding involved first placing the patterns over the dummy mold and sprayed with the parting agent in order to ease with the removal of the patterns.

Figure 16 (a) Mixing plaster into the water to make slurry (b) Curing of plaster mold

Parting line was made by using the thin preformed polymeric sheet over the drag and cope surface in order separate the both mold halves after the curing. After placing the polymeric sheet, the plaster slurry was poured into the bold box and to remove the air bubbles-mold box was been agitated so collect the air bubbles on the upper surface– leaving the casting face free from air holes Figure 16b. Both mold halves were prepared following the same technique.

Mold was left for drying for complete dehydration and proper curing for around 24 hours. After physical dehydration the mold were then pre-heated to temperatures of about 120^{o}C for 20 minutes to accelerate the dehydration and consolidation process between the $CaSO_4$ and water ions. Casting in the prepared preheated plaster mold Figure 17 was then carried out with the pouring temperature as set in the simulation 500^{o}C. The resulted casting was of good quality with smooth surface finish and no visible defects or blow holes on the surface except some hairline marks.

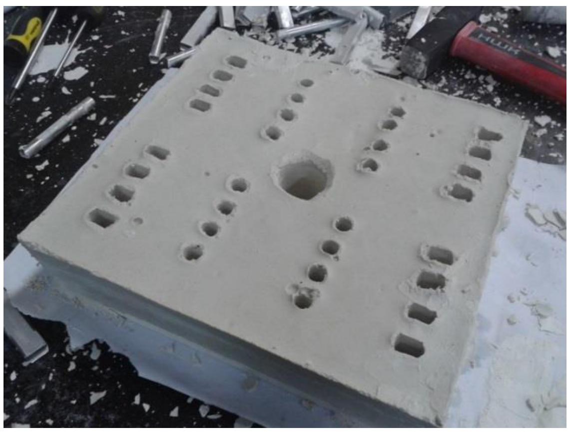


Figure 17 Prepared Plaster mold

5.1.2 Sand Mold Casting

The experimental sequence for the sand mold casting using the two–piece split mold made by "Green Sand" have been carried out with the standard procedures of molding, melting, pouring and casting followed by the instructions in the literature. The molding involved the similar approach as that of plaster molding by first placing the patterns over the dummy mold (braced with acrylic supports) and sprayed with the parting agent in order to ease with the removal of the patterns and dummy mold after the molding. The sand was then rammed over the each opposite pattern face over the parting line Figure 18a to ensure proper filling of the sand in critical details of the pattern.

Figure 18 (a) Preparation of Sand mold (b) Sand mold halves ready for casting

Parting line was made by using the thin preformed polymeric sheet over the drag and cope surface in order separate the both mold halves after the molding operation. Mold ramming required a lot of care to be taken in order to maintain the stability and accuracy in between the two mold halves. Both mold halves were prepared following the same technique and then before the mold closing the mold parting faces were powdered with talc for easy separation Figure 18b. Physical weights (Ingots) were placed over the molds in order to counter the up-thrust upward forces of the molten metal during the pouring. Casting in the prepared sand mold Figure 19 was then carried out with the metal pouring temperature of 500^{o}C.

Figure 19 Sand Mold for casting

The resulted casting was of good quality with smooth surface finish, but lower than the plaster mold casting product. Some visible air and sand particle defects and blow holes have been experienced on the surface of some sand cast samples Figure 20.

Figure 20 Sand mold cast parts

5.1.3 Pattern-less 3D Printed Mold Direct Metal Casting

Ceramic mold prepared by the "3D Printing" Rapid Prototyping Technique has been utilized for the gravity casting of the alloy. Standard techniques for melting, pouring and casting in accordance with the literature for the Z-Cast technique have been adopted. The mold making involved the manufacturing of the pattern-less mold directly from the CAD model of optimized design achieved after the casting simulation Figure 21 for achieving the defect-free cast part.

Figure 21 (a) Optimized 3D Printed Ceramic Mold Design (b) 3D Printed Ceramic Mold for casting

Binder solution during the 3D printing is involved for the consolidation of the printing ceramic powder which is needed to be dried before high temperature pouring inside. So the 3D printed ceramic mold was left to dry for complete dehydration and proper bonding for more than 48 hours. The mold was then pre-heated to temperatures of about 150^{o}C for 1 hour to remove excess moisture in the mold. Casting in the prepared preheated ceramic mold Figure 21 was then carried out with the pouring temperature of 500°C. Prior to closing of the molds the mold parting faces were prepared by sanding the surfaces as swelling was visible which were hindering the complete matching and sitting of cope over drag half.

In place of clamps the mold was supported by the physical weights (Ingots) placed over the molds in order to counter the up-thrust upward forces of the molten metal during the pouring. Due to rough ceramic surface of the mold due to higher grain size of the ceramic powder the surface finish of the casting was not of good quality with grainy surface texture. The cast product surface quality achieved from all the casting processes. Visible ceramic particle defects have been analyzed on the surface of several ceramic cast samples Figure 22. Some parts were incompletely filled due to the availability of small pouring cup not capable to accommodate the metal enough to fill the mold completely.

Figure 22 Ceramic Mold casting

5.2 Validation of Simulated Results by Material Characterization

Validation of the simulation results is done by quality analysis of cast products using the material characterization techniques. The critical portion of the casting shown porosity defects in the simulation results were tested for the porosity at cross section by observing it under optical microscope and found that the casting is free from porosity or any other visible defects. Figure 23 illustrates the critical region and corresponding tested site for casting without porosity in the microstructure of the TEKALOY casting at that region. So the simulation results have been validated by the real casting.

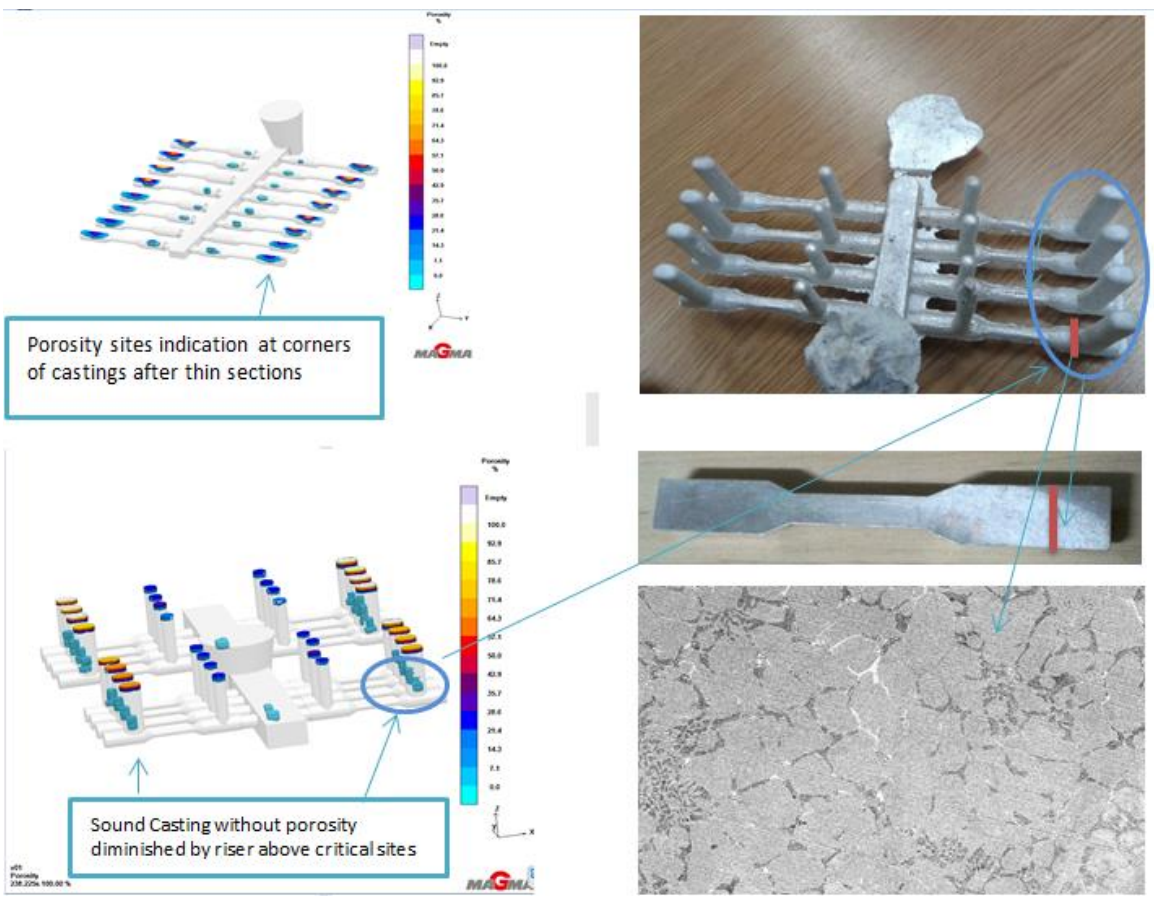


Figure 23 Illustration of the critical region in simulation and corresponding tested site for casting without porosity in the microstructure of the TEKALOY casting

CHAPTER 6

SPIN CASTING OF ZINC ALLOY

In order to compare the quality of the gravity cast products with the recommended practice for the TEKALOY ZA-I, the exactly the same geometry was casted by the spin casting process. This chapter has been designed to fulfill the task 3 to study the spin casting process.

6.1 Spin Casting (Semi-Centrifugal Casting)

Spin casting is a process of semi centrifugally cast the polymers, waxes, low melting metals and alloys in a Silicon rubber molds made by the vulcanization process. The molds are made of Room Temperature Vulcanized (RTV) rubber and organic Silicon rubber, which are flexible enough to accommodate the manual alterations on its faces and are able to sustain temperatures upto 450°C [44, 45]. The molten material is then casted in that molds by the action of centrifugal force of sufficient magnitude to fill the cavities and intricate details inside the mold properly. [46]. This process is particularly suitable for the casting of small parts having intricate details, thin walls and require surface finish which is comparable to the die-cast products.

The spin casting process is an attractive alternative of conventional die-casting, and investment casting technique for the manufacturing of functional and decorative parts with low melting alloys [47]. For the low melting metals like Zinc, Pewter, Lead and Tin, etc., spin casting is a feasible, economical and faster casting method [48]. Among these metals the zinc alloys are most commonly used alloy due to their good resistance against sliding and wear, in combination with good machinability and excellent corrosion resistance in various environments [49-52], which is inherited by Zamak alloys by the presence of copper and aluminum in its zinc matrix, while aluminum also improves the flow properties which facilitates the casting process [53]. The most critical drawback in the spin casting is the lower thermal conductivity of the mold. So the cooling of the molds is a necessary option to enhance the casting properties and dimensional stability which could be optimized by using finite element numerical model in order to accurately simulate and predict the cooling process during the casting phase.

6.2 Experimental Setup

Spin casting process involves several steps including the: 1) Designing a layout of a mold (which is basically a planned organization of the parts to be cast around the center of the mold). 2) The proper material selection for the pattern. 3) The selection of Mold material which depends upon the material of the casting to be made. 4) The preparation of casting cavities in the Rubber mold, which is made up of synthetic organic rubber or synthetic inorganic silicon rubber, is done using the original part, pattern, or the 3D prototype model made by rapid prototyping technique like FDM or 3D Z- Printer [54]. The mold material is usually silicon rubber which can withstand temperatures up to 420°C [55] and some modified rubbers can sustain temperatures up to 538°C, that's why all the metals and alloys like zinc, tin, pewter and lead whose melting temperature occurs under this range can easily be manufactured by spin casting. 5) The mold is then vulcanized by using specially designed vulcanizer in which pressure and temperature is simultaneously applied to get the desired shape of the cavity inside the mold. 6) After vulcanizing the mold is then placed in the spin casting machine, in which the molten metal is then poured from the top of the mold through sprue. Each stage of production has been debated in detail in the impending sections.

In conventional casting processes, mold making is considered as one of the most expensive phases of the entire product development cycle. To reduce the mold production cost and time some non-conventional technologies are being deployed by the foundry technologist instead of using conventional methods of mold making Figure 24. The mold making needs a standard part, or a master pattern made of (Metal, polymer or Composite) by conventional machining process, or by rapid prototyping techniques (3D printing, FDM, SLS, SLA, etc.) [56-59]. The synthetic inorganic silicon rubber mold Figure 1 has been used, first forming the two pancakes shaped upper and lower parts of the mold, same as cope and drag in cast iron mold using in sand casting. The pattern is then laid out on the uncured mold faces around the outer parameter of the mold evenly to balance the centrifugal forces exerted on the metal during casting and the cavities are then made by cutting using the knife.

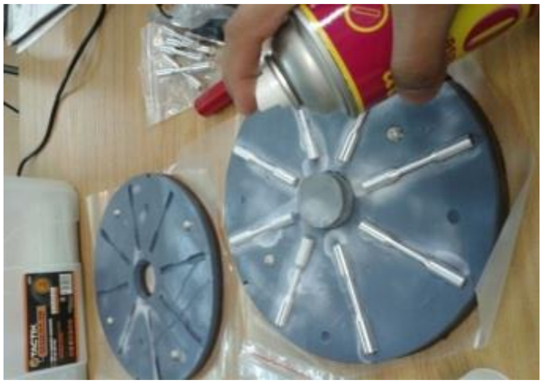


Figure 24 Silicon Rubber Mold with the patterns inside it ready to be vulcanized

As a general practice the patterns are placed between 5–8 cm from each other and 3-6 cm from the outside of the mold and 6-7 cm from the center of the mold in order to protect the dimensional stability of the mold during the casting. Sprue is made by placing the center plug ring in the center of the mold disk. And to ensure proper placement and to avoid misalignment in casting, locknuts are installed on the required positions. The mold is then sprayed with Teflon or ceramic mold parting spray. After spraying the patterns then placed and pressed into the mold.

The mold is then placed between the ring frames and vulcanized by placing it in the TEKCAST vulcanizing Press Figure 25. Initially heat and pressure were applied to the vulcanizer for required period of time in order to set the pattern into the mold cavity firmly and then this cycle is repeated several times. This procedure is called "bumping the mold", which allows entrapped air in the mold to release when dropping the pressure to zero. The vulcanizing time and temperature depends on the thickness of the mold. The recommended vulcanization temperature for conventional silicone rubber mold is 170^{O}C, and the pressure recommended for vulcanizing is between 14 and 35 MPa depends on the mold's dimensions [60].

Application of the heat and pressure on the mold tends the uncured silicon rubber to surround the patterns perfectly and fill the empty positions resulting in the manual cutting. Also for online monitoring the temperature of the mold during the casting process thermocouple can be placed inside the mold. [59].

Figure 25 Mold vulcanizing setup including the TEKCAST vulcanizer machine with press

The mold after vulcanizing is hard, and dimensionally stable close to the actual part. After vulcanization, the patterns can easily be removed from the vulcanized mold cavities. In last, the runner and gating system Figure 26 with proper air venting (for removal of entrapped gases) are formed by cutting the proper dimension in the mold according to the experience [61, 62]. The quality of the casting product is much dependent on the proper placement of the runner, riser, sprue and gating mechanism. For this purpose special care has been taken in making the running and gating system in order to avoid any possible casting defects and improper filling of the cavities [62, 46]. The mold is then sprayed with parting powder and then it can be used for several cycles of production based on the type of alloy casted and the process parameters.

Figure 26 Running and gating system of the mold

The mold is then placed inside the front loading Spin air Caster Figure 27 for the casting of the required molten metal. The actuating assembly is then activated to clamp the mold with required pressure, with the selection of the operational parameters (Casting time, Mold Clamping Pressure and the spinning speed), depending on the material and dimensions of the castings [63] as the response of materials differs from each other. Like for metals, the spinning time is lesser than the plastics due to their flow properties and filling times. The process flow of the whole spin casting process adopted in this study has been illustrated in Figure 5.

Figure 27 Front loading Spin Caster

It is the action of centrifugal force during spinning, exerted on the molten metal to be filled in the mold cavities and fills critically thin spaces and intricate details. After the casting is finished the clamping pressure is released and the mold is removed. With careful handling, the runner and gating system can easily be removed manually without need of any machinery but little grinding or polishing may be required to remove runners and gates from actual casting and to get required surface finish.

6.3Semi-Centrifugal Spin Casting Experimental Studies

Besides the gravity casting processes, the spin casting experiments have also been carried out for the comparative qualitative analysis with the gravity casting processes. Standard operating Procedures mentioned in prior section have been adopted for the preparation of mold Figure 28 by vulcanizing and the final casting using the spin caster Figure 29(a).

Figure 28 Spin Casting silicon mold

The spin casting was performed with the same mold utilizing multiple times without any visible distortion or thermal degradation during the spin casting operation. Final casting sets Figure 29(b) have been obtained at different operating parameters varying mainly the casting temperature, rotational speeds and spinning time. Detailed analysis report has been illustrated in Table 5.2.

Figure 29 (a) Spin Casting Setup, (b) Spin Cast sample sets casted at varying Parameters

CHAPTER 7

PARAMETRIC ANALYSIS OF SPIN CASTING: STUDYING PROCESS CAPABILTIES AND LIMITATIONS

The following chapter highlights the parametric study of the spin casting process to study the process capabilities and limitations of the process in details with the help of experimentation in accordance to fulfill the task 3.1. Primarily, the main motivation behind this study is to develop two predictive models for the quality indicators of spin cast product: porosity and tensile strength in order to be utilizing for the optimization of the spin cast product quality in order to accomplish our task 3.2.

7.1 Process Capabilities and Limitations

The possible factors involves in deciding the final quality of the casting product have been listed and discussed in details in this section adopted from the previous literature. For desired quality and integrity of casting product Clamping pressure, rotational speed, geometry and size of the cavity, temperature of mold and the materials and casting material all factors are equally important to control the casting overall quality and dimensions. In general, it is recommended to carry out the casting at the lowest possible mold clamping pressure, rotational speed and the mold temperature, for a consistency in the cavity filling. Other factors that affect the quality of the spin casting consists of but not limited to proper design of running and gating system, design of the mold, and the cooling rate of the melting material, thermal gradients, part geometry and the type of the material used for casting and of the mold.

7.2 Parametric Analysis of Spin Casting Process

Comprehensive qualitative and quantitative analysis have been done for the spin cast samples obtained at different process parameters to have a comprehensive data to elucidate the parametric influence on the cast products. Table 8 illustrates the operating parametric sets inducted to apply design of experiments method to the spin cast products.

The optimal parametric combination set can easily be sort out by using the design of experiment techniques in the industry. The fixed values for each parameter cannot be suggested for getting the optimized quality of spin cast product, as it wholly depends upon the acceptance criteria of the quality department and can only be picked with the mutual agreement and the requirements of the customer. And also the selection of the process parameters depends upon the level of quality with the appropriate combination of mechanical and physical properties and soundness required in the final spin cast product.

In short the design of experiment technique adopted here, provide relevant data set to decide the optimized parameters including mainly the mold holding pressure, rotation time and the mold spinning velocity for the casting of the required part which cannot be generalized for parts of nearly similar shapes.

Table 8 Operating Parametric Sets inducted for the Design of Experiments

Sample	Pressure (psi)	Time (s)	Rotation Speed (rpm)	Temperature (^oC)
SA-1	45	30	375	390
SA-2	45	30	425	390
SA-3	45	30	500	390
SA-4	45	30	600	390
SA-5	45	40	375	390
SA-6	45	40	425	390
SA-7	45	40	500	390
SA-8	45	40	600	390
SA-9	45	50	375	390
SA-10	45	50	425	390
SA-11	45	50	500	390
SA-12	45	50	600	390
SA-13	45	60	375	390
SA-14	45	60	425	390
SA-15	45	60	500	390
SA-16	45	60	600	390
SS-1	45	30	375	420
SS-2	45	30	425	420
SS-3	45	30	500	420
SS-4	45	30	600	420
SS-5	45	40	375	420
SS-6	45	40	425	420
SS-7	45	40	500	420
SS-8	45	40	600	420
SS-9	45	50	375	420
SS-10	45	50	425	420
SS-11	45	50	500	420
SS-12	45	50	600	420
SS-13	45	60	375	420
SS-14	45	60	425	420
SS-15	45	60	500	420
SS-16	45	60	600	420
SI-1	45	30	375	450
SI-2	45	30	425	450
SI-3	45	30	500	450
SI-4	45	30	600	450
SI-5	45	40	375	450
SI-6	45	40	425	450
SI-7	45	40	500	450
SI-8	45	40	600	450
SI-9	45	50	375	450
SI-10	45	50	425	450
SI-11	45	50	500	450
SI-12	45	50	600	450
SI-13	45	60	375	450
SI-14	45	60	425	450
SI-15	45	60	500	450
SI-16	45	60	600	450
SM-1	45	30	375	480
SM-2	45	30	425	480
SM-3	45	30	500	480
SM-4	45	30	600	480
SM-5	45	40	375	480
SM-6	45	40	425	480
SM-7	45	40	500	480
SM-8	45	40	600	480
SM-9	45	50	375	480
SM-10	45	50	425	480
SM-11	45	50	500	480
SM-12	45	50	600	480
SM-13	45	60	375	480
SM-14	45	60	425	480
SM-15	45	60	500	480
SM-16	45	60	600	480

Statistical analysis for the optimization of the process parameters to achieve higher dimensional accuracy by reducing the dimensional errors with the help of polynomial regression model, variance and standard deviation analysis in conjunction with design of experiment approach is an intelligent investigation method to monitor the data information for total quality control management system. The similar approach has been utilized in this study for getting reliable statistics of the spin cast parts as it is crucial for the batch mechanical parts in the production line to maintain a certain dimensional accuracy monitored and maintained with a production record by the Quality Assurance department in industry.

To test the quality aspects of the TEKALOY spin cast parts different experiments with varying process parameters (Time, Temperature, Pressure and Rotational Speeds) Table 8 have been carried out in order to find out the effect of these varying parameters on the porosity, hardness and the dimensional integrity. The design of experiment approach (DOF) has been adopted to monitor the influence of process parameters on the quality of parts in terms of percent porosity, the total volume change and the mechanical strength in terms of hardness. Useful data has been achieved through these statistical analyses which can surely be used as valuable resources to improve the quality of the spin casting products.

Dimensional Accuracy and Structural Integrity: Segregation of the dimensional data has been done with the intention to assess the percent volumetric reduction of the TEKALOY ZA-1 samples, collected with varying combinations of process parameters Table 8. The measurements were carried out using conventional dimensional measuring tools with the dimensional accuracy of 10μm. The volumetric deviation trend has been calculated as illustrated in Figure 30 which indicates that the samples 1, 6, 7, and 10 showed the higher volumetric reductions with the lower rotational time and the greater speeds with sample 6 having the highest value. While the variations are on the lowest side in case of the samples 11, 12, and 16 with higher mold spin time and the mold spinning speeds with sample 16 with the lowest volumetric reduction. The linear dimensional accuracy has been previously identified and optimized by using the numerical optimization methods (polynomial regression model) in several studies.

In order to optimize the casting parameters to get sound casting in the lab with good dimensional accuracy and close geometrical tolerance statistical analysis has been integrated with this study. The statistical analysis done in Table 9 helps to find out the standard deviation and variance of the volumetric deviations in order to reduce the dimensional errors.

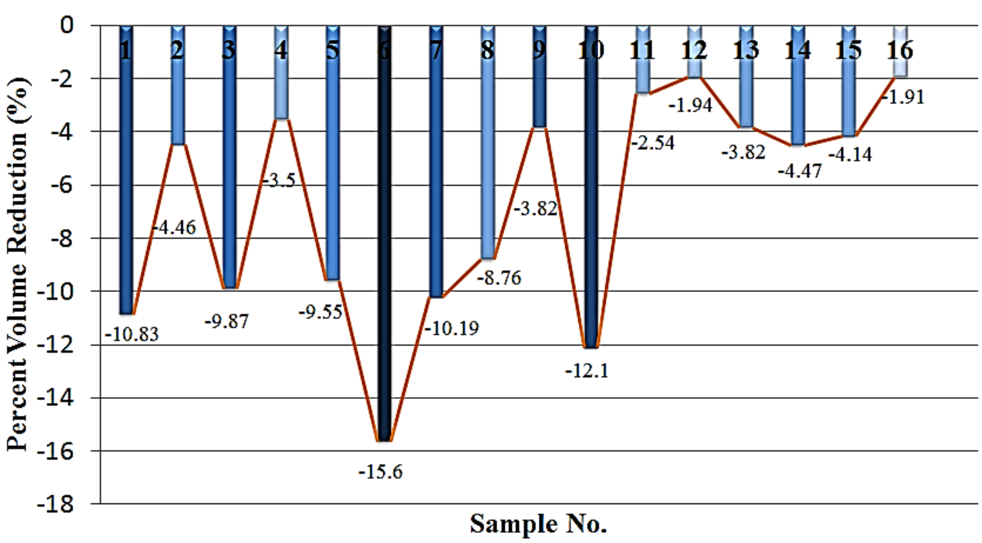


Figure 30 Trend followed by Percent Volume Reduction in each Test Sample

Through statistical Analysis it has been found that the samples 6 and 10 shows the maximum deviation in dimensions of 0.2138, while some of the sample indicates the deviations of 0.1138 while the other most of the samples lies in the deviation range of about -0.083.

Percent Porosity Measurements: To analyze the structural integrity of the spin cast product at varying process parameters the percent total porosity has been computed by **"bulk density methods"** and further verified by the **"SEM analysis".**

The porosity trend for each sample combination Figure 31 shows that the samples with the tags 2, 13, and 14 possess the higher total porosity content with the higher rotational time and the greater speeds with highest porosity content 13% found in sample 13. While the porosity is on the lower side in the samples tagged 3, 6, and 8 with lower rotation time and at medium speeds, sample 3 represents the lowest total porosity content with 30 seconds spin time and 500 rpm rotational speed and the decreasing porosity profile at higher speeds and time.

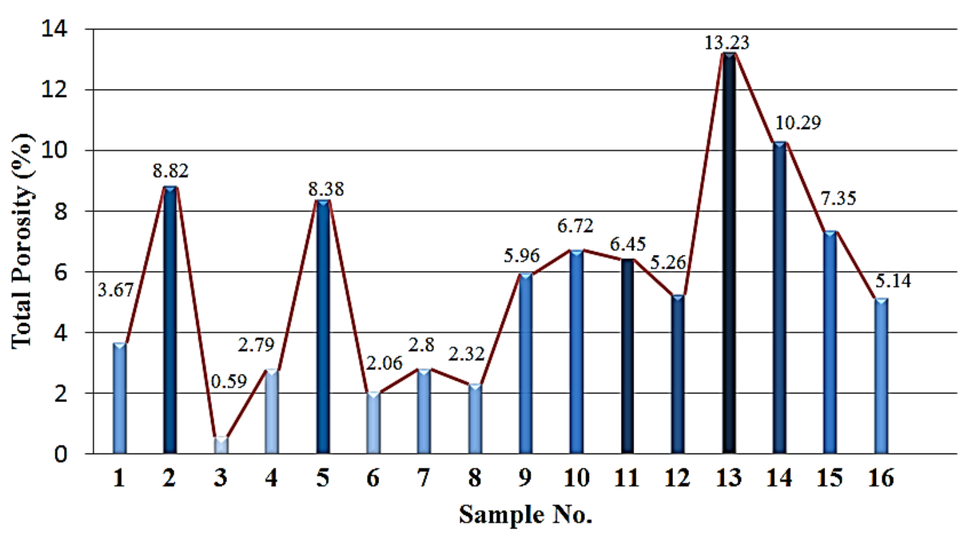


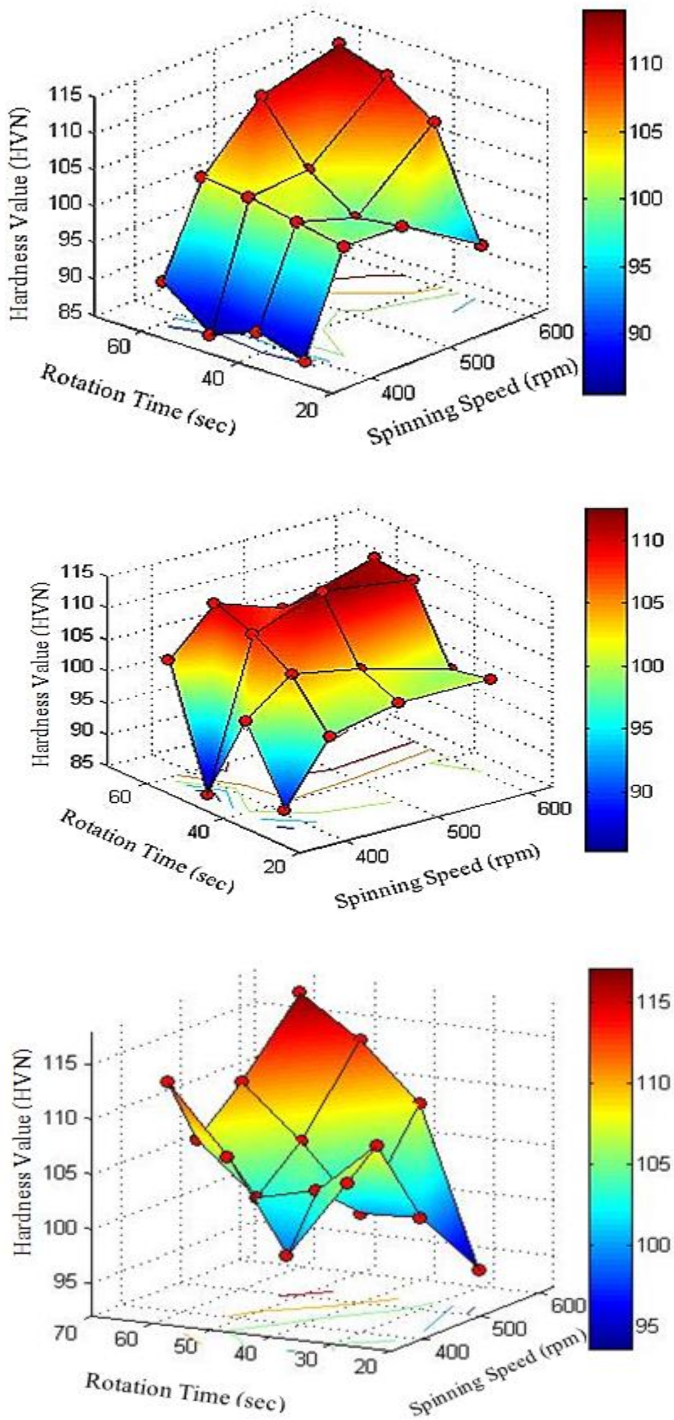
Figure 31 Trend followed by Percent Total Porosity in each Test Sample

Considering the rotational speed as one of the major parameters involve in the porosity control of the casting, the direct relation graph has been plotted to find out the trend and contribution of rotational speed on the porosity content at various mold rotation times. Similar porosity reducing trend can be observed at 550 revolutions, irrespective of the mold spinning time indicating the lower factor contribution in the porosity control.

Table 9 Statistical Analysis of Spin cast parts' volumetric shrinkage values with calculated Standard deviation and the variance results to reduce the dimensional error

	Sample no.	Volumetric Change (a)	Deviation about the mean (b)	(b2)
	1	0.34	0.1138	0.0129
	2	0.14	-0.0863	0.0074
	3	0.34	0.1138	0.0129
	4	0.14	-0.0863	0.0074
	5	0.34	0.1138	0.0129
	6	0.44	0.2138	0.0457
	7	0.34	0.1138	0.0129
	8	0.14	-0.0863	0.0074
	9	0.14	-0.0863	0.0074
	10	0.44	0.2138	0.0457
	11	0.14	-0.0863	0.0074
	12	0.14	-0.0863	0.0074
	13	0.12	-0.1063	0.0113
	14	0.14	-0.0863	0.0074
	15	0.14	-0.0863	0.0074
	16	0.14	-0.0863	0.0074
Total		**3.62**	**-7.77156E-16**	**0.2214**
Number of Samples		**16**		**16**
Mean Value		**0.2263**		
Variance				**0.0148**
Standard Deviation				**0.1215**

Hardness Testing: As for mechanical strength the hardness values have been measured using the Vickers hardness tester. It can be observed that a hardness values are increased at corresponding higher mold rotational velocities. Figure 32 (a-d) illustrates the hardness profiles at different casting temperatures and varying speeds and spinning time with temperature increment of 30 degrees above melting. This analogous trend has been followed throughout the spinning time range Figure 38 by each combination of casted test samples 1- 4 (30 seconds), 5-8 (40 seconds), 9-12 (50 seconds) and 13-16 (60 seconds).



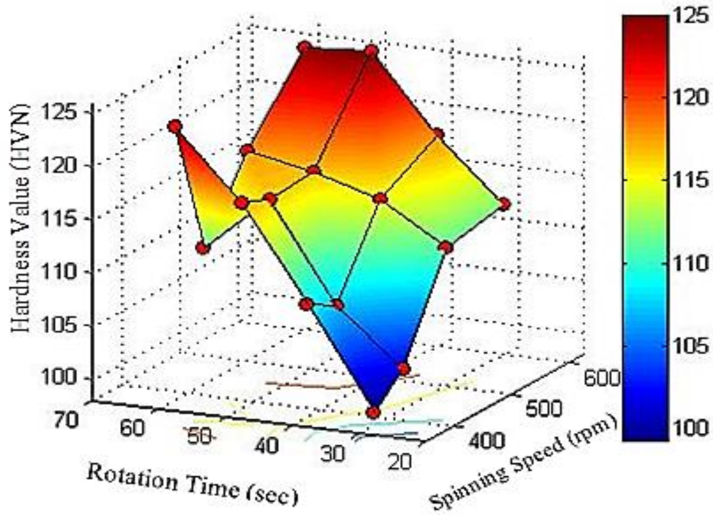


Figure 32 (a-d) illustrates the hardness profiles at different casting temperatures and varying speeds and spinning time with temperature increment of 30 degrees above melting TEKALOY ZA-1

Longer rotation time and higher spinning mold speed tend to increase the cooling effect in the molten metal facilitates the formation of the smaller grain size and hence more grain boundaries are formed at the microstructure of the TEKALOY ZA-I alloy during spin casting. This increase in the number of the grain boundaries, suppressed grain growth and faster cooling effect are the favorable characteristics for the increment in the hardness values of the metal. This behavior has been observed in Figure 33 and 34, in which the hardness values increment is noticeable at all test mold spinning times.

The optimization of the casting completed with finding the best parametric combination for getting the sound TEKALOY ZA-1 casting with the test design.

The optimal parametric combination set can easily be sort out by using the design of experiment techniques in the industry. The fixed values cannot be suggested as it wholly depends upon the acceptance criteria of the quality department and can only be picked with the mutual agreement and the requirements of the customer.

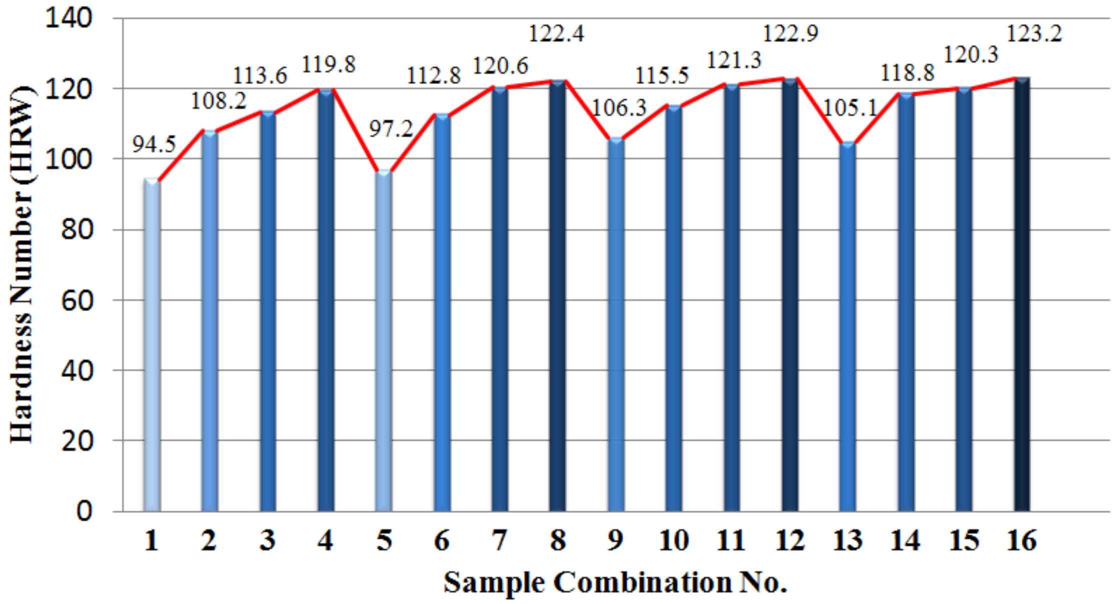


Figure 33 Trend followed by mechanical hardness values in each Test Sample displaying increase in the hardness with the speed in each sample combination set of spinning time.

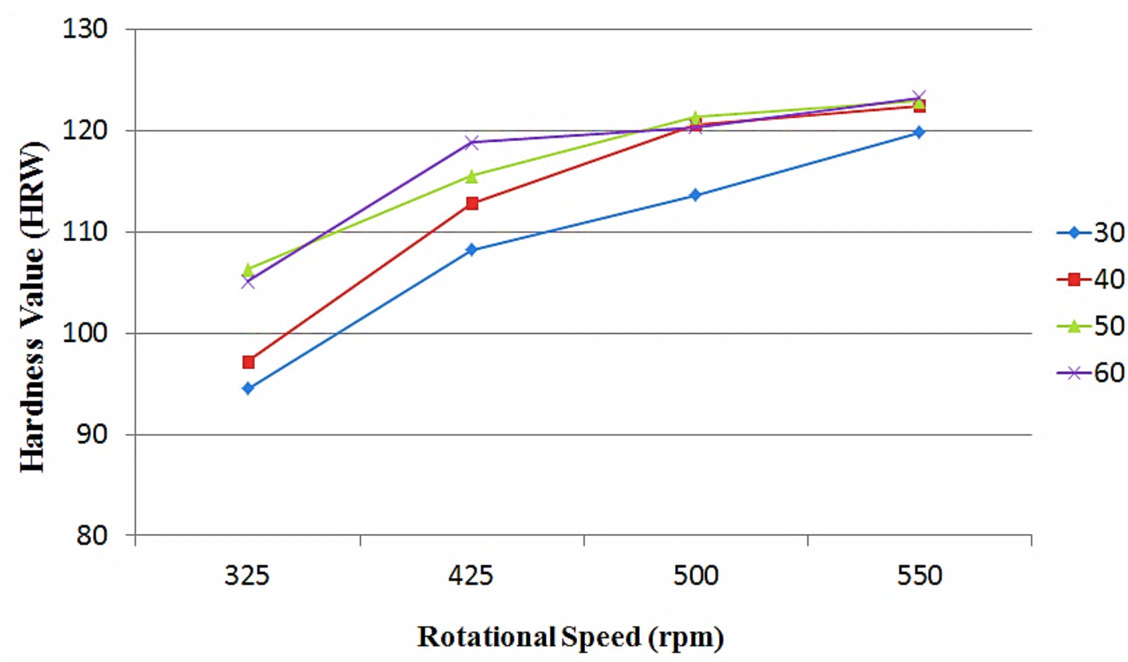


Figure 34 Trend illustrating direct contribution of the rotational speed and time on the hardness values of TEKALOY ZA-1

In short the design of experiment technique adopted here, provide relevant data set to decide the optimized parameters including mainly the mold holding pressure, rotation time and the mold spinning velocity for the casting of the required part which cannot be generalized for parts of nearly similar shapes. The results for optimizing the dimensional accuracy can be comprehended with the ternary surface plot in Figure 35. In this plot the profile elucidates the intensity of the discrete and simultaneous effects of processing parameters on the volumetric deviation of each TEKALOY sample.

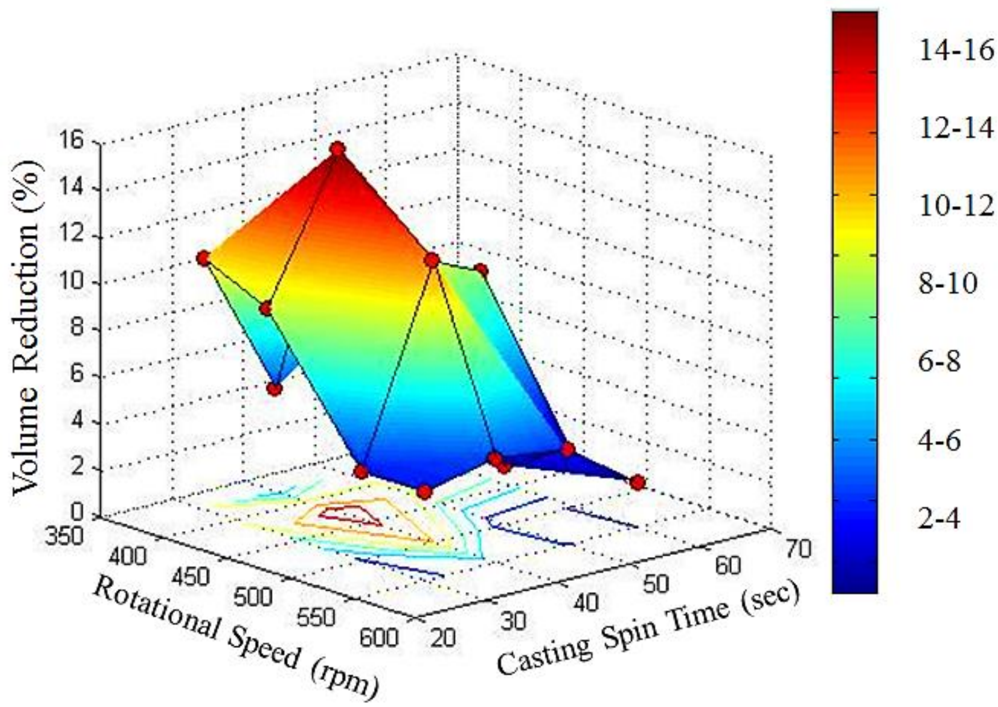


Figure 35 Ternary Surface plot illustrating the simultaneous and individual effects of the mold rotation velocity and the spinning time on the volume

7.3Predictive Models Development for Porosity and Tensile Strength

Besides the parametric studies of the spin casting process, two predictive models have been developed for the porosity and tensile strength of the spin cast products that can be utilize in future for designing a FEM software for the casting simulation of the Spin

Casting process for optimization of the cast quality and process for getting the sound cast product.

Furthermore two parametric models have been predicted in efforts to utilize them in introducing a spin casting simulation software. Through these models the parametric data can be utilized for predicting the final cast product quality by input the processing parameters.

7.3.1 Predictive Model for Porosity

First multiple regression model has been developed by for the prediction of amount of porosity in the spin cast product w.r.t the seven independent processing parameters, the porosity model which has been found can be written as equation below:

ln P = 4.12189 + 0.195445 ln N + 0.86809 ln T +0.218209 ln Y – 0.838629 ln.t – 0.449311 ln E – 1.01659 ln Hd-0.289842 ln UTS (5.1)

The above porosity model can be written as:

$$\boldsymbol{P = 61.69\ \frac{N^{0.195445}.T^{0.86809}.Y^{0.218209}}{t^{0.838629}.E^{0.449311}.Hd^{1.01659}.UTS^{0.289842}}} \qquad (5.2)$$

Where, ***P*** is the % Porosity, ***N*** is the Rotational speed in rpm, ***T*** is the Temperature in **°C**, ***Y*** represents the Yielding Stress (MPa), ***t*** denotes the mold spinning time in seconds, ***E*** is the % Elongation, ***Hd*** represents the Hardness in (HVN) and the ***UTS*** represents the Ultimate Tensile Strength in MPa.

Since the P-values in the ANOVA Tables 10 and 11 are less than 0.05, there is statistically significant relationship between the variables at the 95% confidence level.

The R-squared static indicates that the model as fitted explains 39.3625% of the variability in ln porosity. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 31.7828%. The standard error of the estimate shows the standard deviation of the residuals to be 0.474698. This value can be used to construct prediction limits for new observations. The Mean Absolute Error (MEA) of 0.360388 is the average value of the residuals. The statistical report for the above multiple regression model is given below:

Table 10 Summary Table of the Process Variables

Parameter	***Estimate***	***Standard Error***	***T Statistic***	***P-Value***
CONSTANT	4.12189	6.26307	0.657125	0.5132
ln Time	-0.838629	0.298338	-2.811	0.0068
ln Rotational Speed	0.195445	0.42619	0.458586	0.6483
ln Temperature	0.86809	1.20016	0.723312	0.4725
ln Elongation	-0.449311	0.237126	-1.89481	0.0633
ln Hardness	-1.01659	1.17621	-0.86429	0.3911
ln Yield Stress	0.218209	0.71734	0.304192	0.7621
ln Tensile Strength	-0.289842	0.645533	-0.448997	0.6552

Table 11 ANOVA Report for the relationship between ln porosity and Process Variables

Analysis of Variance					
Source	***Sum of Squares***	***D_f***	***Mean Square***	***F-Ratio***	***P-Value***
Model	8.19151	7	1.17022	5.19	0.0001
Residual	12.6189	56	0.225338		
Total (Corr.)	20.8104	63			

R-Squared = 39.3625 %.
R-Squared (adjusted for d. f.) = 31.7828 %
Standard Error of Estimate = 0.474698
Mean Absolute Error = 0.360388
Durbin-Watson Statistic = 1.57439 (P = 0.0178)
Lag 1 residual autocorrelation = 0.209312

The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on order which they occur in the data. Since the P-value is less than 0.05, there is an indication of possible serial correlation at the 95.0 % confidence level. The Table 12 below shows the statistical significance of each variable as added to the model.

Table 12 Conditional Sums of Squares illustrating the statistical significance of each process variables

Further ANOVA for Variables					
Source	*Sum of Squares*	*D_f*	*Mean Square*	*F-Ratio*	*P-Value*
ln Time	4.14353	1	4.14353	18.39	0.0001
ln Rotational Speed	0.0205644	1	0.0205644	0.09	0.7637
ln Temperature	0.637411	1	0.637411	2.83	0.0982
ln Elongation	3.00118	1	3.00118	13.32	0.0006
ln Hardness	0.220352	1	0.220352	0.98	0.3270
ln Yield Stress	0.123051	1	0.123051	0.55	0.04630
ln Tensile Strength	0.0454278	1	0.0454278	0.20	0.6552
Model	8.19151	7			

The Table 13 below shows 95% confidence intervals for the coefficient in the model. Confidence intervals show how precisely the coefficient can be estimated given the amount of available data and the noise which is present.

Table 13 Confidence intervals for the coefficients in the model

95% Confidence Intervals for Coefficient Estimates				
Parameter	*Estimate*	*Standard Error*	*Lower Limit*	*Upper Limit*
CONSTANT	4.12189	6.26307	-8.42458	16.6684
ln Time	-0.838629	0.298338	-1.43627	-.0240985
ln Rotational Speed	0.195445	0.42619	-0.658319	1.04921
ln Temperature	0.86809	1.20016	-1.53612	3.2723
ln Elongation	-0.449311	0.237126	-0.924333	0.0257116
ln Hardness	-1.01659	1.17621	-3.37283	1.33965
ln Yield Stress	0.218209	0.71734	-1.2188	1.65522
ln Tensile Strength	-0.289842	0.645533	-1.583	1.00332

The following data Table 14 shows the estimated correlations matrix between the coefficients fitted in the model and the porosity. In the table it is clarified that there are 5 correlations with absolute values greater than 0.5, which shows serious multicollinearity amongst the process variables (mold spinning time, metal pouring temperature, hardness and rotational speeds, etc.).

Table 14 Showing the multicollinearity matrix amongst the process variables

Correlation Matrix for Coefficient Estimates (Part-I)				
	CONSTANT	***ln Time***	***ln Rotational Speed***	***ln Temperature***
CONSTANT	1.0000	-0.2180	-0.3562	-0.8337
ln Time	-0.2180	1.0000	0.3538	0.2823
ln Rotational Speed	-0.3562	0.3538	1.0000	0.3298
ln Temperature	-0.8337	0.2823	0.3298	1.0000
ln Elongation	0.2404	-0.2907	-0.0864	-0.0829
ln Hardness	0..2126	-0.4971	-0.5748	-0.6312
ln Yield Stress	-0.1416	-0.3328	-0.1332	0.2451
ln Tensile Strength	0.0880	0.3616	0.1329	-0.1940

Continued… (Part-II)				
	ln Elongation	***ln Hardness***	***ln Yield Stress***	***ln Tensile Strength***
CONSTANT	0.2404	0.2126	-0.1416	0.0880
ln Time	-0.2907	-0.4971	-0.3328	0.3616
ln Rotational Speed	-0.0864	-0.5748	-0.1332	0.1329
ln Temperature	-0.0829	-0.6312	0.2451	-0.1940
ln Elongation	1.0000	-0.1007	0.7237	-0.7533
ln Hardness	-0.1007	1.0000	-0.1014	0.0684
ln Yield Stress	0.7237	-0.1014	1.0000	-0.9827
ln Tensile Strength	-0.7533	0.0684	-0.9827	1.0000

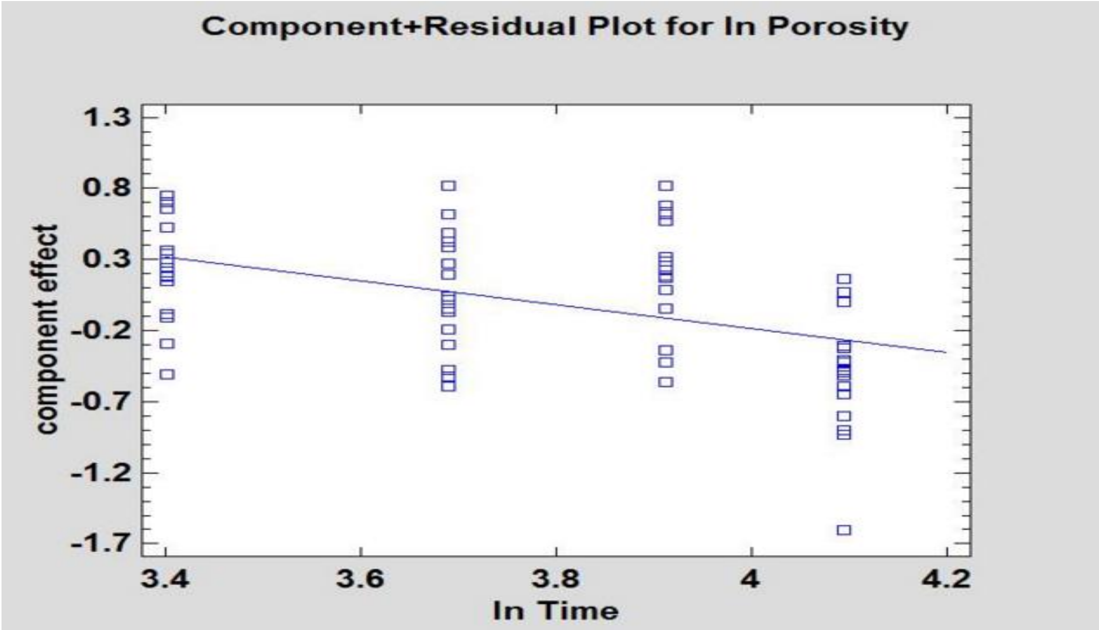


Figure 36 Component Effect plot for the Spinning Time on the ln Porosity

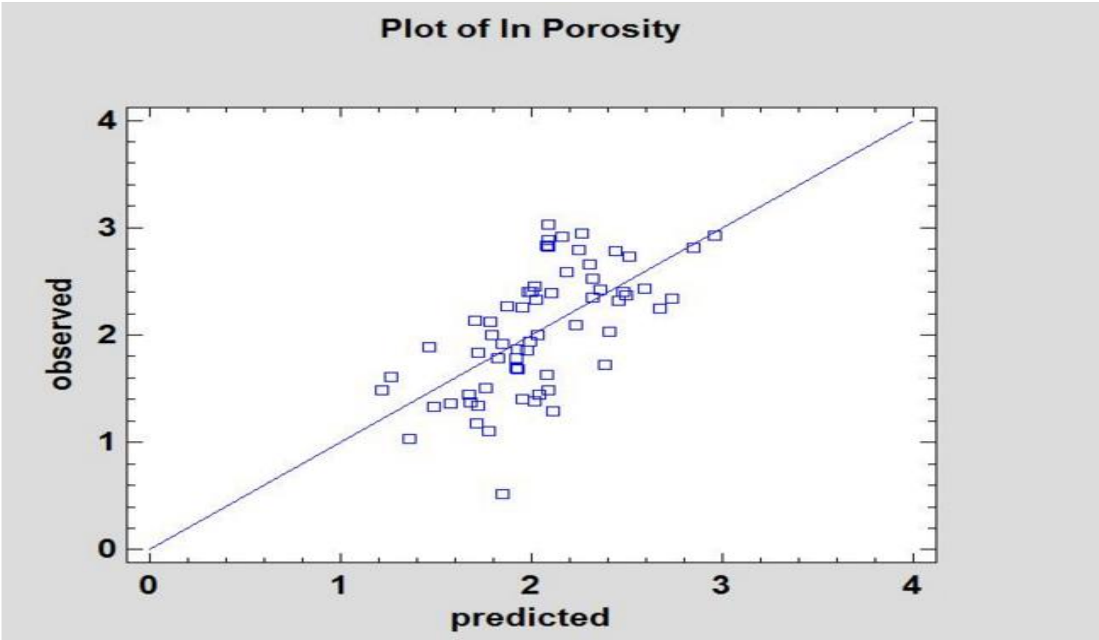


Figure 37 Observed vs. predicted values curve for the ln porosity

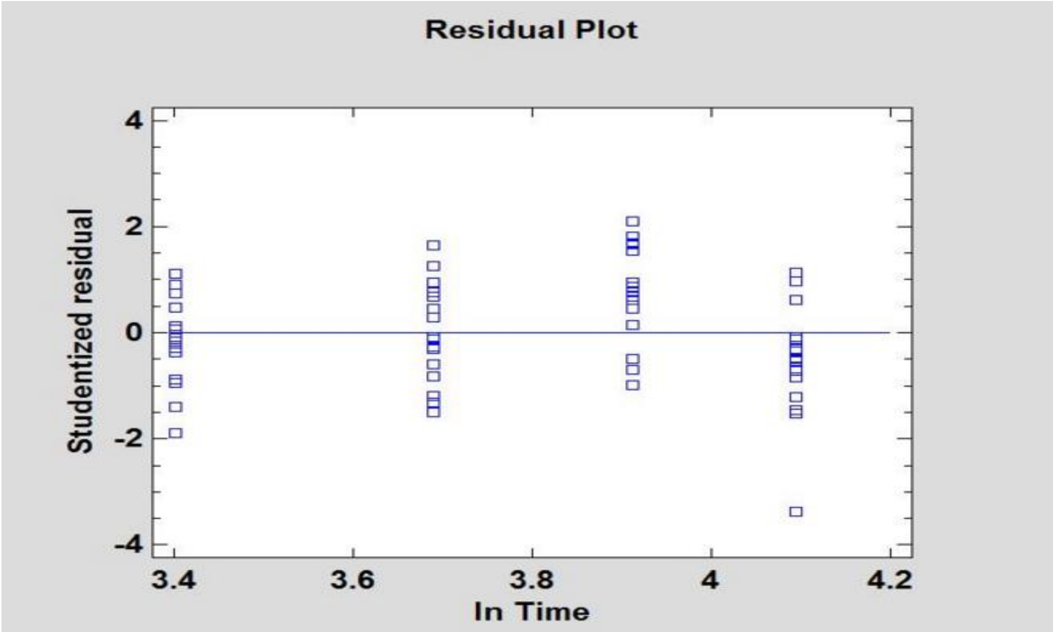


Figure 38 Residual Plot representing the difference of observed and predicted Spinning times

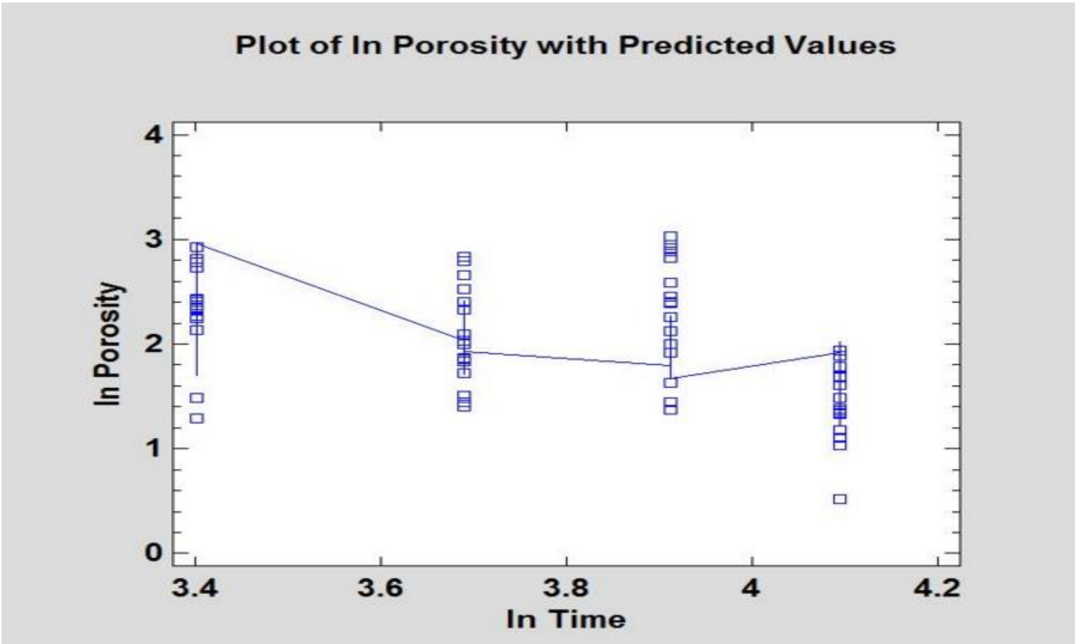


Figure 39 Residuals versus Predicted plot illustrating the relationship of ln porosity with the spinning time

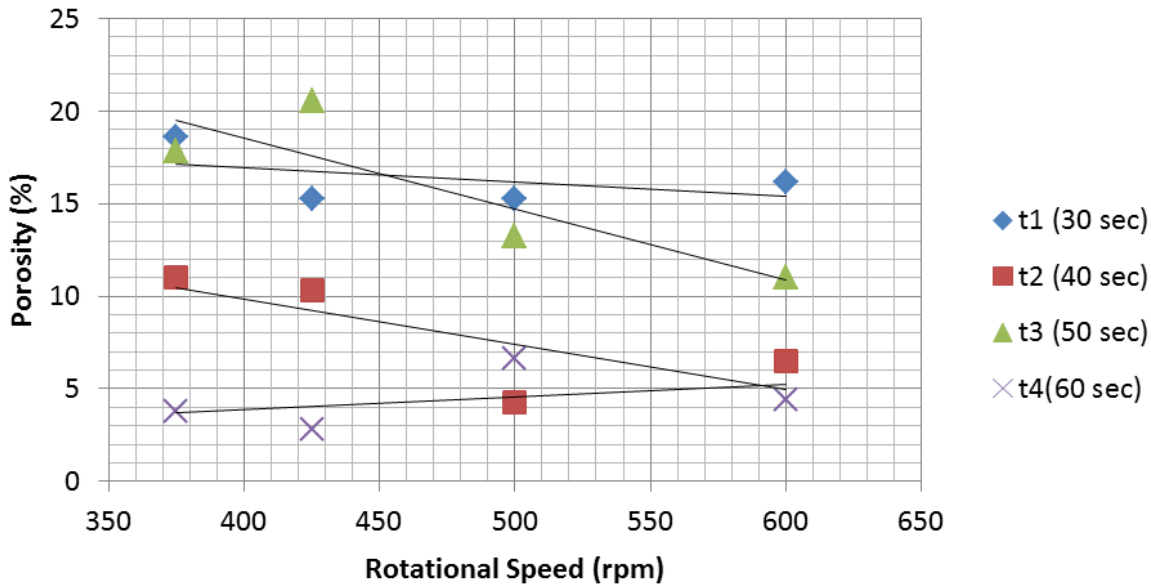


Figure 40 Parametric Relationship between porosity and Rotational speeds at different time

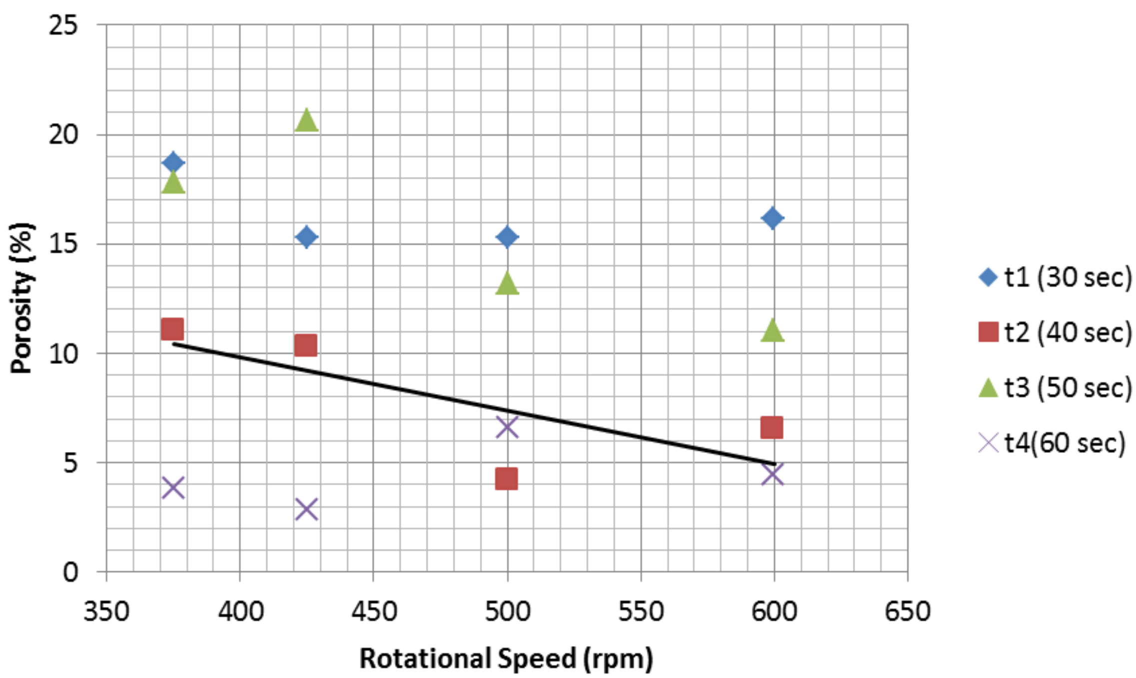


Figure 41 Discrete Distribution and Mean deviation of porosity at varying Rotational speeds and time

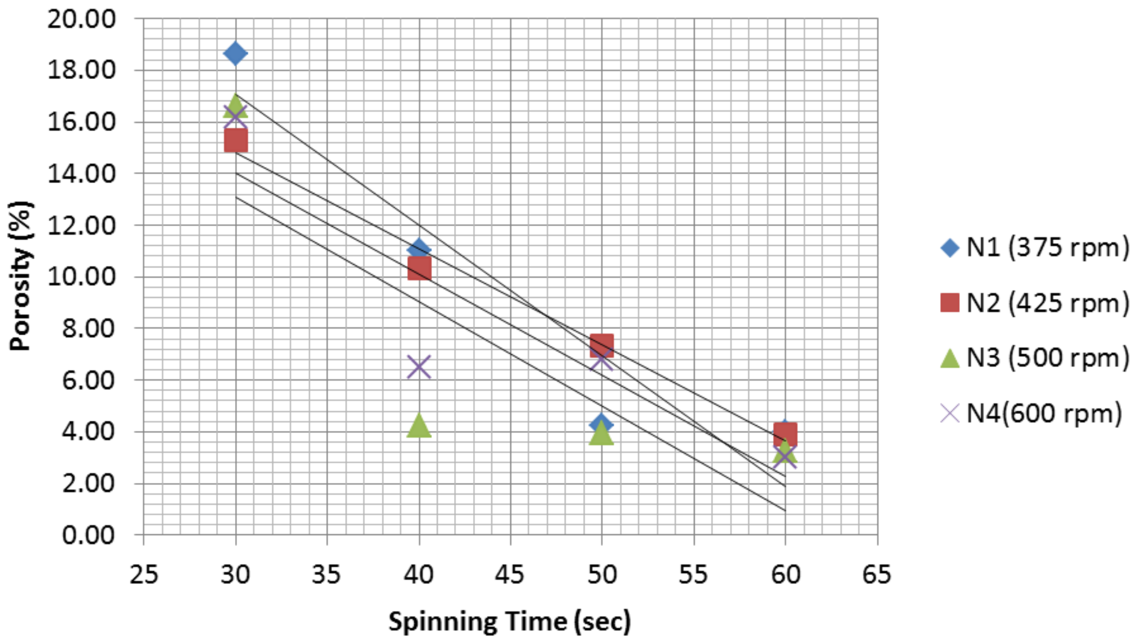


Figure 42 Parametric relationships between porosity and Spinning time at different speeds

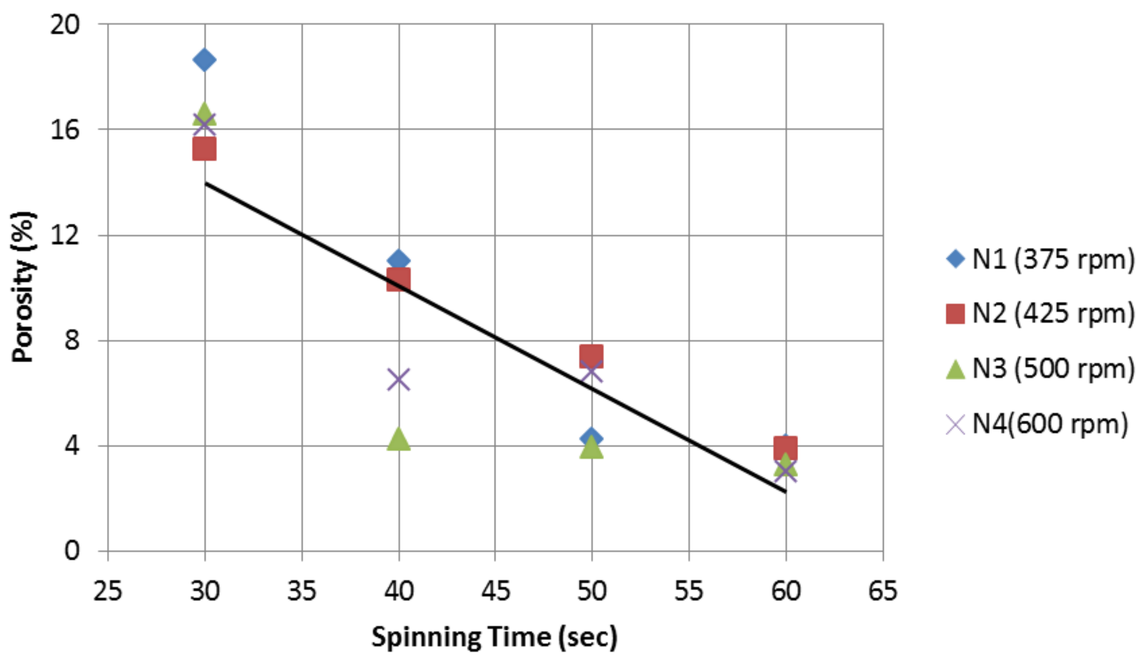


Figure 43 Discrete Distribution and Mean deviation of porosity at varying Spinning Time and speeds

7.3.2 Predictive Model for Tensile Strength

Second multiple regression model which has been developed for the prediction of tensile strength in the spin cast product w.r.t the processing parameters, the strength model which has been found can be written as:

ln UTS = - 0.799807 + 1.09075 ln Y + 0.270173 ln E - 0.0123759 ln P – 0.176902 ln t – 0.0850094 ln N – 0.370037 ln T - 0.136841 ln Hd (5.3)

The above model can be written in simplified form as:

$$\mathbf{UTS} = -2.225\ \frac{Y^{1.09075}.E^{0.270173}}{t^{0.176902}.P^{0.0123759}.Hd^{0.136841}.N^{0.0850094}.T^{0.370037}} \tag{5.4}$$

Where, ***UTS*** represents the Ultimate Tensile Strength in MPa, ***N*** is the Rotational speed in rpm, ***T*** is the Temperature in ^{o}C, ***Y*** represents the Yielding Stress (MPa), ***t*** denotes the mold spinning time in seconds, ***E*** is the % Elongation, ***Hd*** represents the Hardness in (HVN) and the ***P*** is the % Porosity.

The statistical summary report for the above multiple regression model has been illustrated in the Table 15 below:

Table 15 Summary Table of the Process Variables

Parameter	Estimate	Standard Error	T Statistic	P-Value
CONSTANT	-.0799807	1.29477	-0.617721	0.5393
ln Porosity	-0.0123759	0.0275634	-0.448997	0.6552
ln Time	-0.176902	0.0614642	-2.84814	0.0057
ln Rotational Speed	-0.0850094	0.0874974	-0.971565	0.3354
ln Temperature	0.370037	0.244196	1.51533	0.1353
ln Elongation	0.270173	0.0353747	7.63747	0.0000
ln Hardness	-0.136841	0.24398	-0.560872	0.5771
ln Yield Stress	1.09075	0.0276177	39.4947	0.0000

Table 16 ANOVA Report for the relationship between ln UTS and Process Variables

Analysis of Variance					
Source	*Sum of Squares*	D_f	*Mean Square*	*F-Ratio*	*P-Value*
Model	18.2446	7	2.60637	270.89	0.0000
Residual	0.538811	56	0.00962163		
Total (Corr.)	18.7834	63			

R-Squared = 97.1314 %.
R-Squared (adjusted for d. f.) = 96.7729 %
Standard Error of Estimate = 0.0980899
Mean Absolute Error = 0.0631322
Durbin-Watson Statistic = 1.87223 (P = 0.1838)
Lag 1 residual autocorrelation = 0.0611504

Since the P-values in the ANOVA table above are less than 0.05, there is statistically significant relationship between the variables at the 95% confidence level.

The R-squared static indicates that the model as fitted explains 97.1314% of the variability in ln Tensile strength. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 96.7729%. The standard error of the estimate shows the standard deviation of the residuals to be 0.0980899. This value can be used to construct prediction limits for new observations. The Mean Absolute Error (MEA) of 0.0631322 is the average value of the residuals.

The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on order which they occur in the data. Since the P-value is less than 0.05, there is an indication of possible serial correlation at the 95.0 % confidence level. The Table 17 below shows the statistical significance of each variable as it was added to the model by ANOVA.

Table 17 Conditional Sums of Squares illustrating the statistical significance of each process variables

Further ANOVA for Variables					
Source	*Sum of Squares*	D_f	*Mean Square*	*F-Ratio*	*P-Value*
ln Porosity	0.614882	1	0.614882	63.91	0.0000
ln Time	0.680779	1	0.680779	70.76	0.0000
ln Rotational Speed	0.252268	1	0.252268	26.22	0.0000
ln Temperature	0.102081	1	0.102081	10.61	0.0019
ln Elongation	1.20304	1	1.20304	236.04	0.0000
ln Hardness	0.383384	1	0.383384	39.85	0.0000
ln Yield Stress	15.0081	1	15.0081	1559.83	0.0000
Model	18.2446	7			

The Table 18 below shows 95% confidence intervals for the coefficient in the model. Confidence intervals show how precisely the coefficient can be estimated given the amount of available data and the noise which is present.

Table 18 Confidence intervals for the coefficients in the model

95% Confidence Intervals for Coefficient Estimates				
Parameter	*Estimate*	*Standard Error*	*Lower Limit*	*Upper Limit*
CONSTANT	-0.799807	1.29477	-3.39355	1.79394
ln Porosity	-0.0123759	0.0275634	-0.0675921	0.0428404
ln Time	-0.176902	0.0614642	-0.30003	-0.0537745
ln Rotational Speed	-0.0850094	0.0874974	-0.260288	0.0902693
ln Temperature	0.370037	0.244196	-0.119148	0.859223
ln Elongation	0.270173	0.0353747	0.199309	0.341038
ln Hardness	-0.136841	0.24398	-0.625592	0.351909
ln Yield Stress	1.09075	0.0276177	1.03543	1.14608

The data Table 19 shows the estimated correlations matrix between the coefficients fitted in the model and porosity. It is clarified that there are 2 correlations with absolute values greater than 0.5, which shows serious multicollinearity amongst the variables.

Table 19 Showing the multicollinearity matrix amongst the process variables

Correlation Matrix for Coefficient Estimates (Part-I)				
	CONSTANT	ln Porosity	ln Time	ln Rotational Speed
CONSTANT	1.0000	-0.0930	-0.2434	-0.3637
ln Porosity	-0.0930	1.0000	0.3544	-0.0696
ln Time	-0.2834	0.3544	1.0000	0.2840
ln Rotational Speed	-0.3637	-0.0696	0.2840	1.0000
ln Temperature	-0.8210	-0.0862	0.3284	0.3695
ln Elongation	0.3863	0.4126	0.1209	-0.0095
ln Hardness	0.1954	0.1108	-0.4822	-0.5932
ln Yield Stress	-0.3048	0.0981	0.1559	-0.0208
Continued… (Part-II)				
	ln Temperature	ln Elongation	ln Hardness	ln Yield Stress
CONSTANT	-0.08210	0.3863	0.1954	-0.3048
ln Porosity	-0.0862	0.4126	0.1108	0.0981
ln Time	0.3284	0.1209	-0.4822	0.1559
ln Rotational Speed	0.3695	-0.0095	-0.5932	-0.0208
ln Temperature	1.0000	-0.3577	-0.6347	0.2889
ln Elongation	-0.3577	1.0000	-0.0220	-0.0827
ln Hardness	-0.6347	-0.0220	1.0000	-0.1717
ln Yield Stress	0.2889	-0.0827	-0.1717	1.0000

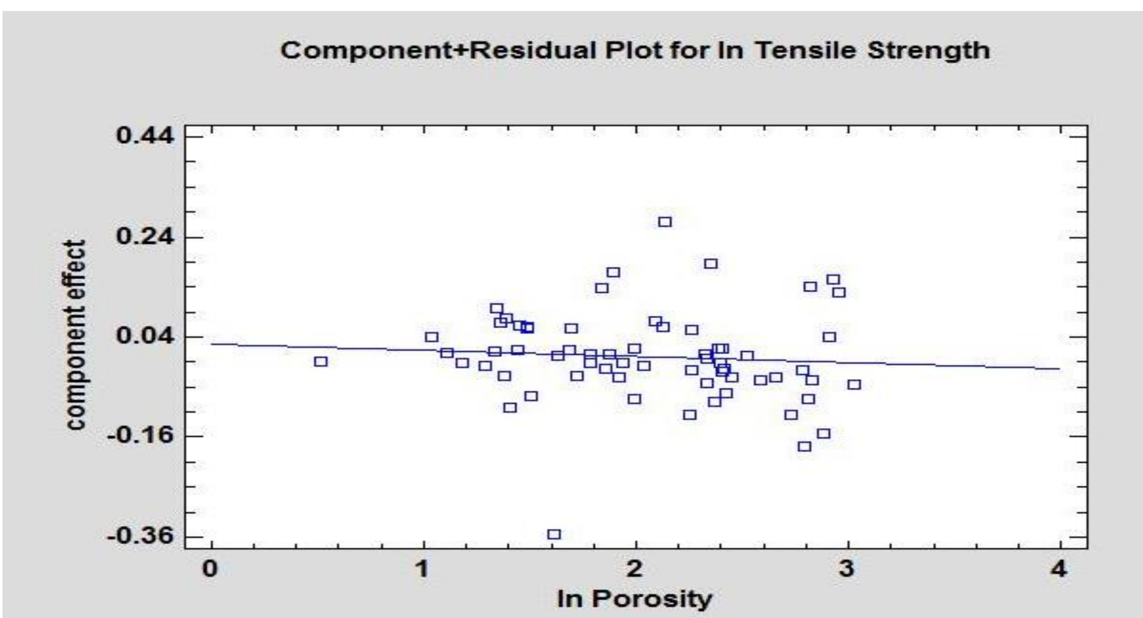


Figure 44 Component Effect plot for the ln porosity on the ln Tensile Strength

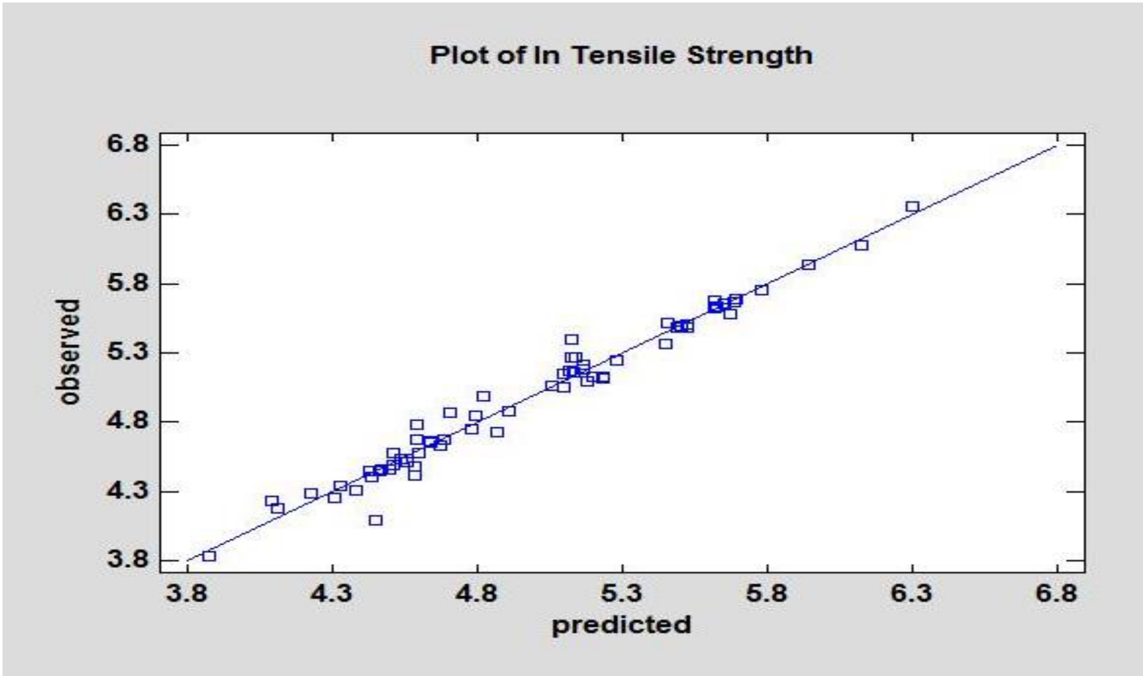


Figure 45 Observed vs. predicted values curve for the ln Tensile Strength

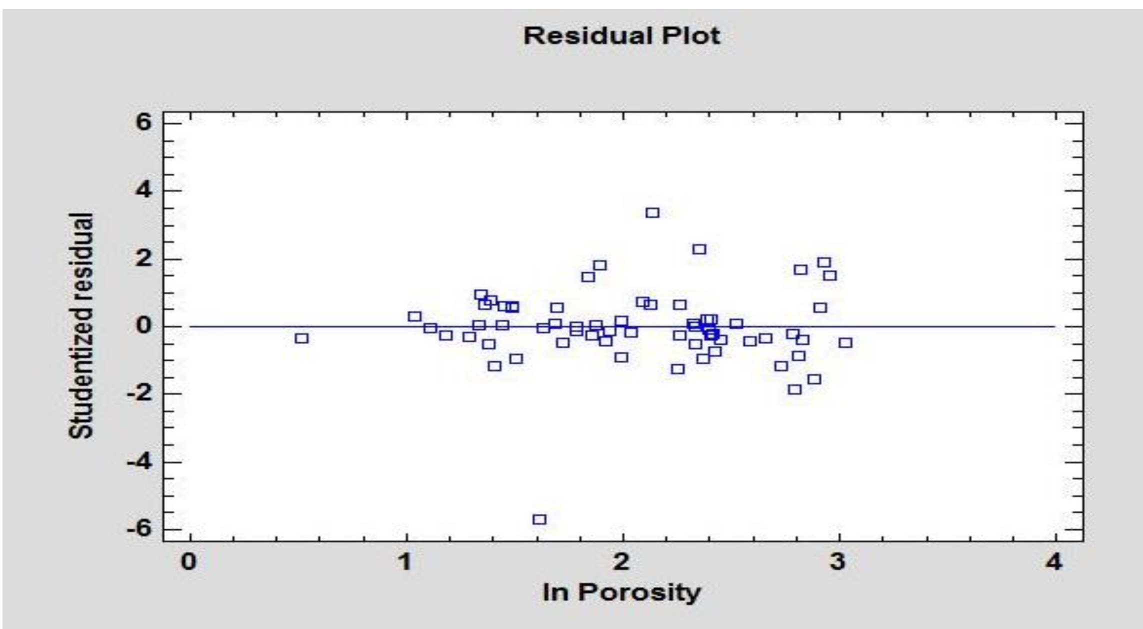


Figure 46 Residual Plot representing the difference of observed and predicted ln porosity level

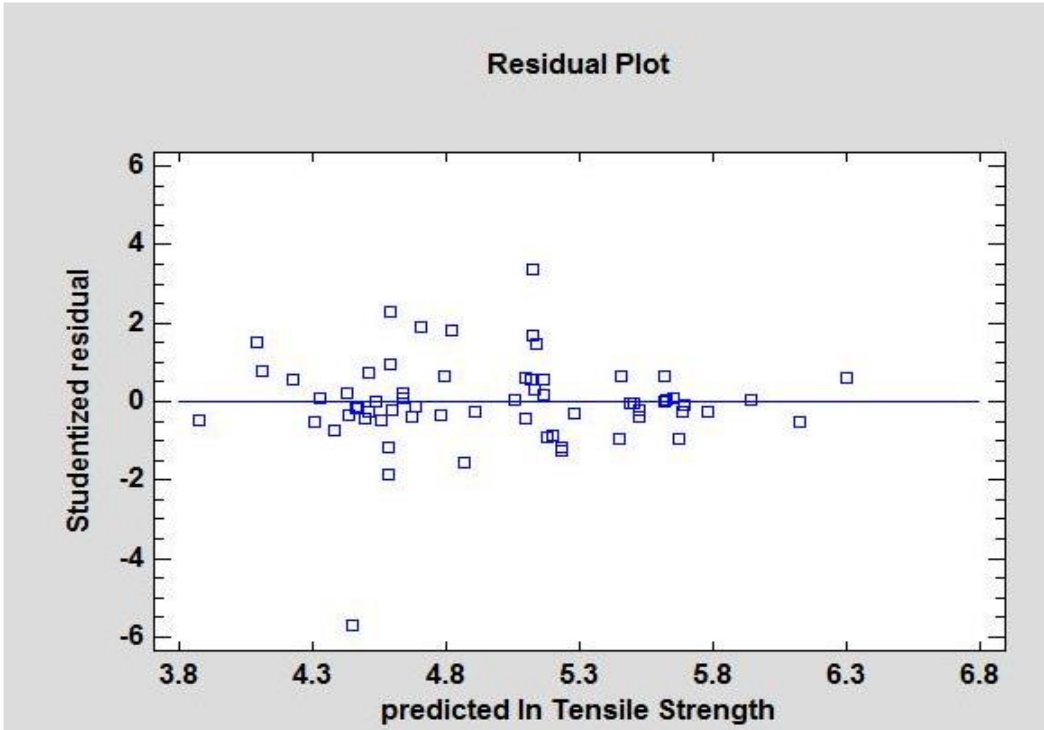


Figure 47 Residuals versus Predicted plot for the ln Tensile Strength values

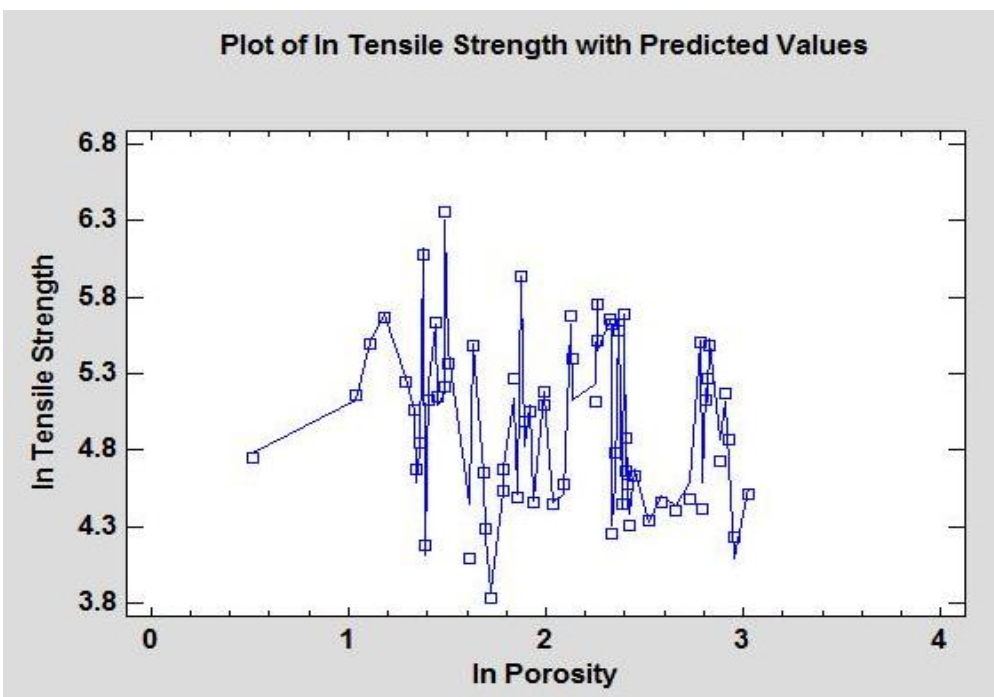
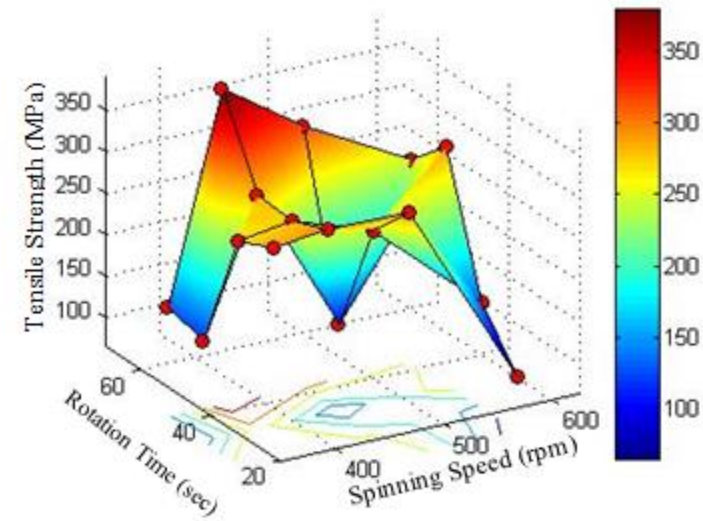


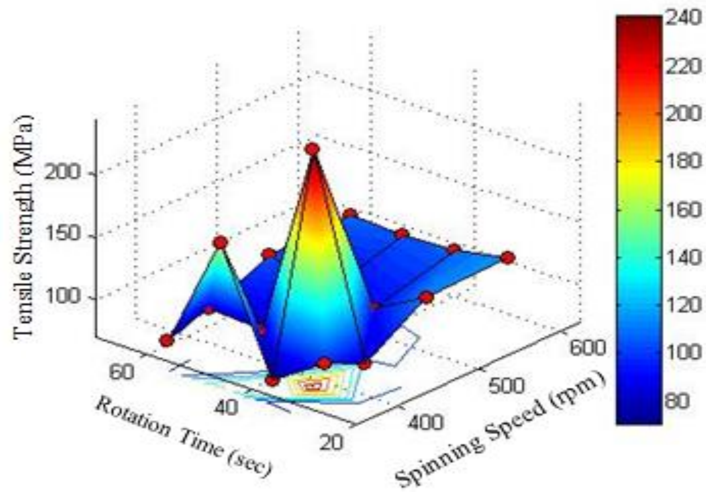
Figure 48 Illustrating the relationship of ln UTS with the predicted values of ln Porosity

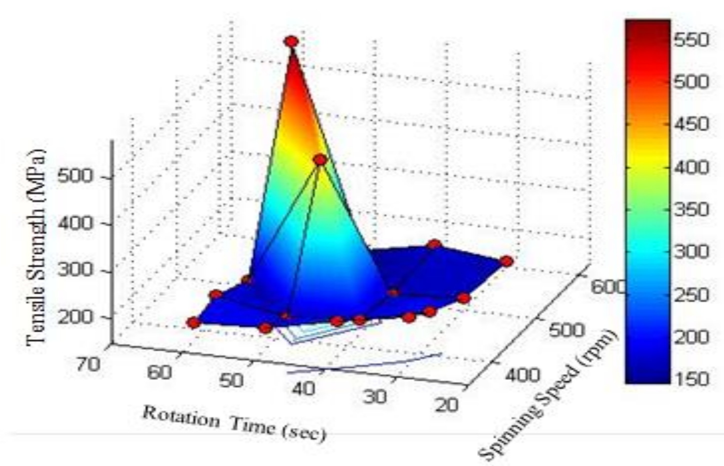
Strength Analysis: For analyzing the mechanical strength of the spin cast TEKALOY ZA-1 samples the tensile strength of several other samples has been measured, which were casted directly from the spin casting process using another specially designed silicon mold Figure 49 for conducting the tensile testing on as-cast parts without machining operation. The tensile test has been carried out using the Instron Universal Testing Machine with standard operating procedures.

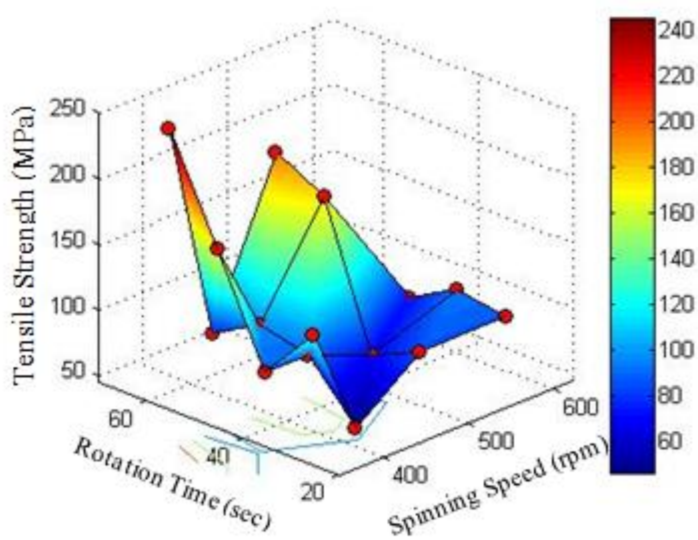
Figure 49 Spin cast Mold for casting the Dumbbell shaped Tensile Test Specimens

TEKALOY ZA-1 castings found to have brittle nature of fracture during the tensile testing as they have shown little amount of plastic deformation with minimal elongation. The samples show brittle cleavage fracture almost perpendicular to the applied tensile stress. Figures 50 (a-d) shows the tensile strength profiles for the spin cast samples casted at melting temperature then at 3 times 30 degrees increments. For getting the optimum tensile strength of the alloy, it is required to have optimum combination of process parameters including the rotational speed, time and temperature, the increasing trend of tensile strength for the TEKALOY ZA-1 spin cast parts as function of increase rotational speeds is shown in Figure 51.


Tensile Strength (MPa)
Rotation Time (sec)
Spinning Speed (rpm)


Tensile Strength (MPa)
Rotation Time (sec)
Spinning Speed (rpm)


Tensile Strength (MPa)
Rotation Time (sec)
Spinning Speed (rpm)



Figures 50 (a-d) shows the tensile strength profiles for the spin cast samples casted at different temperatures with increment of 30 degrees.

Besides, porosity-strength relationship has been analyzed for the spin cast samples casted at constant temperature of 390°C in order to quantify the tensile strength value for increasing porosity content of material. Figure 55 illustrates the porosity-strength profile for spin cast samples. Variable profile can be seen in the graph with the results showing that the samples with higher porosity content possess the lower tensile strength. Keeping in mind that the tensile strength is also much dependent on other spin casting process parameters like rotational speed and time, etc. as discussed before.

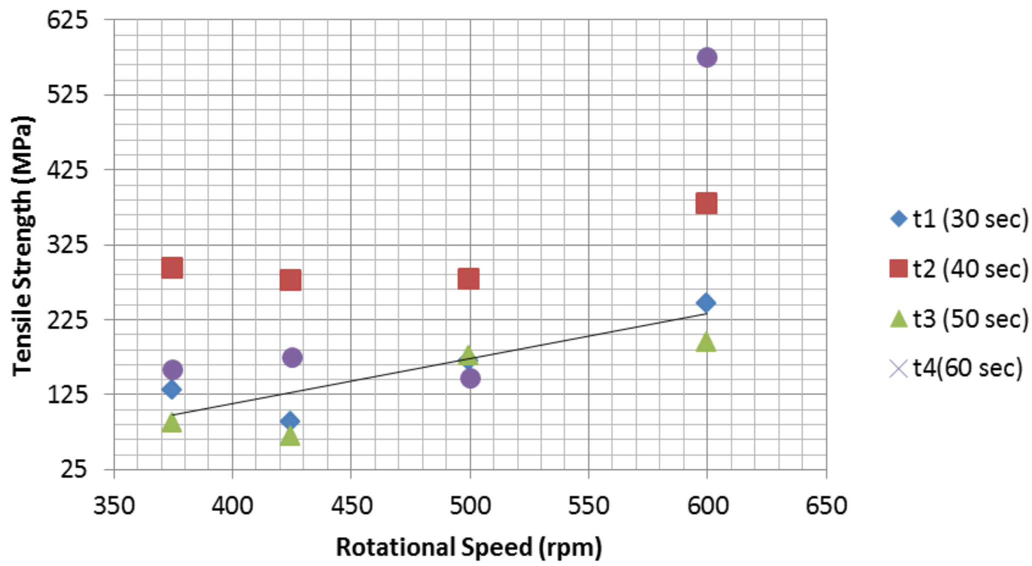


Figure 51 Tensile Strength profile for the spin cast samples casted at varying speeds and spinning time.

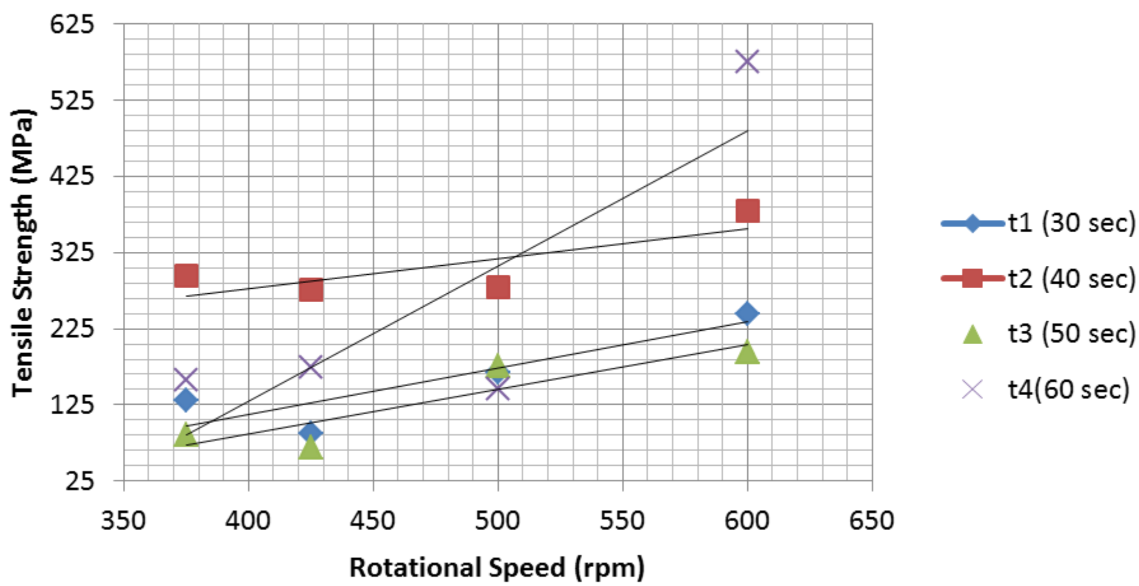


Figure 52 Parametric relationships between Tensile Strength and Rotational speeds at different time

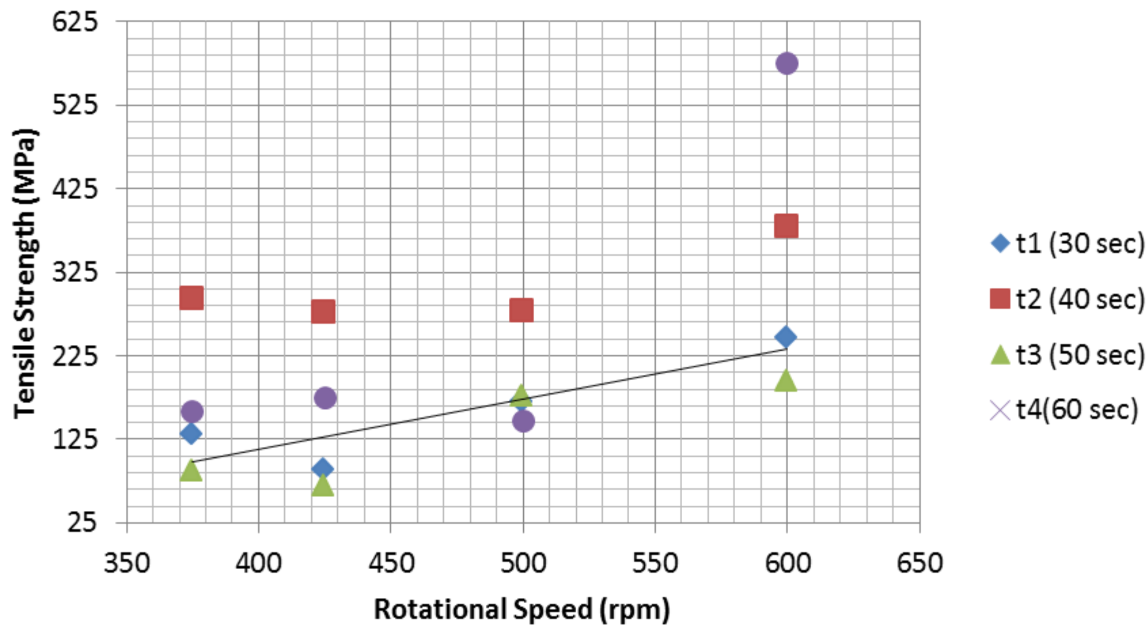


Figure 53 Discrete Distribution and Mean deviation of Strength at varying Rotational speeds and time

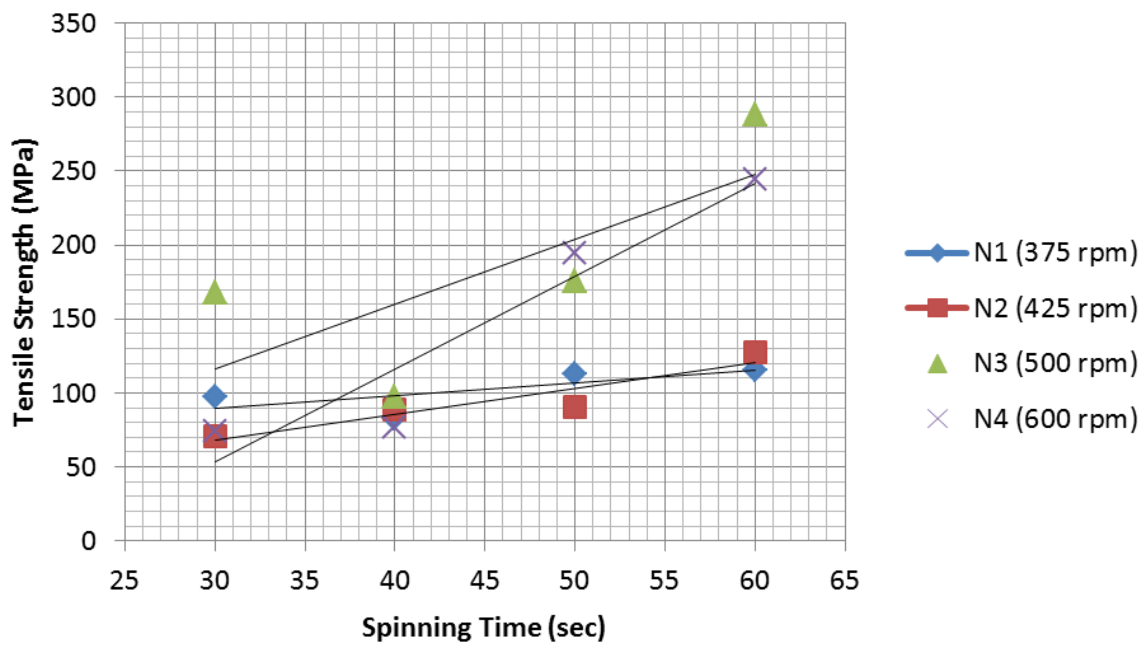


Figure 54 Parametric relationships between Tensile Strength and Spinning time at different speeds

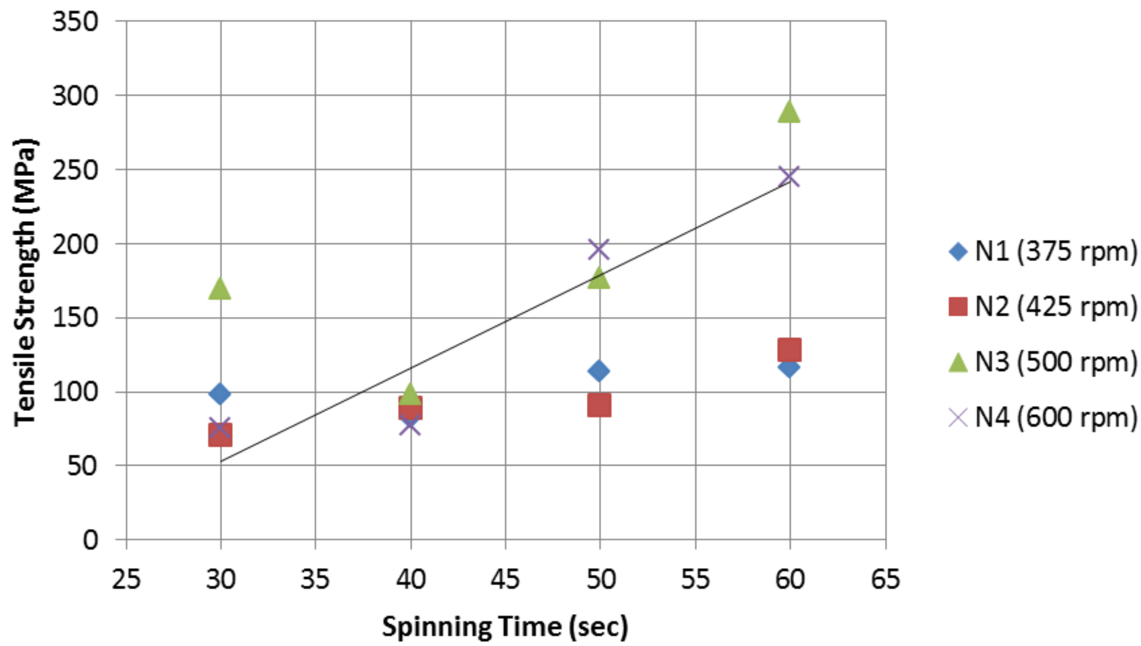


Figure 55 Discrete Distribution and Mean deviation of Strength at varying Spinning Time and speeds

For getting the optimum tensile strength of the alloy, it is required to have optimum combination of process parameters including the rotational speed, time and temperature, the increasing trend of tensile strength for the TEKALOY ZA-1 spin cast parts as function of increase rotational speeds is shown in Figure 51, 52, 53 and 54.

Besides, porosity-strength relationship has been analyzed for the spin cast samples casted at constant temperature of 390°C in order to quantify the tensile strength value for increasing porosity content of material. Figure 56 illustrates the porosity-strength profile for spin cast samples.

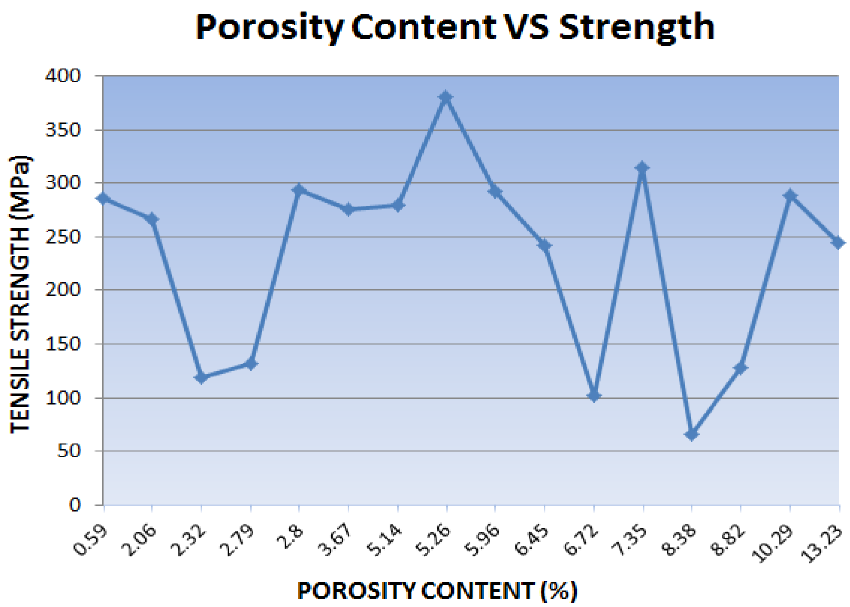


Figure 56 Porosity-Tensile Strength trend for the spin cast samples casted.

Variable profile can be seen in the graph with the results showing that the samples with higher porosity content possess the lower tensile strength. Keeping in mind that the tensile strength is also much dependent on other spin casting process parameters like rotational speed and time, etc. as discussed before.

CHAPTER 8

QUALITY ASSESSMENT OF CAST PRODUCTS

Finally the qualitative comparative analysis has been done for the castings in order to get in-depth knowledge and assess the cast products for their integrity. The castings have been examined by Materials Characterization techniques, Mechanical testing, and tested for the dimensional accuracy and surface finish.

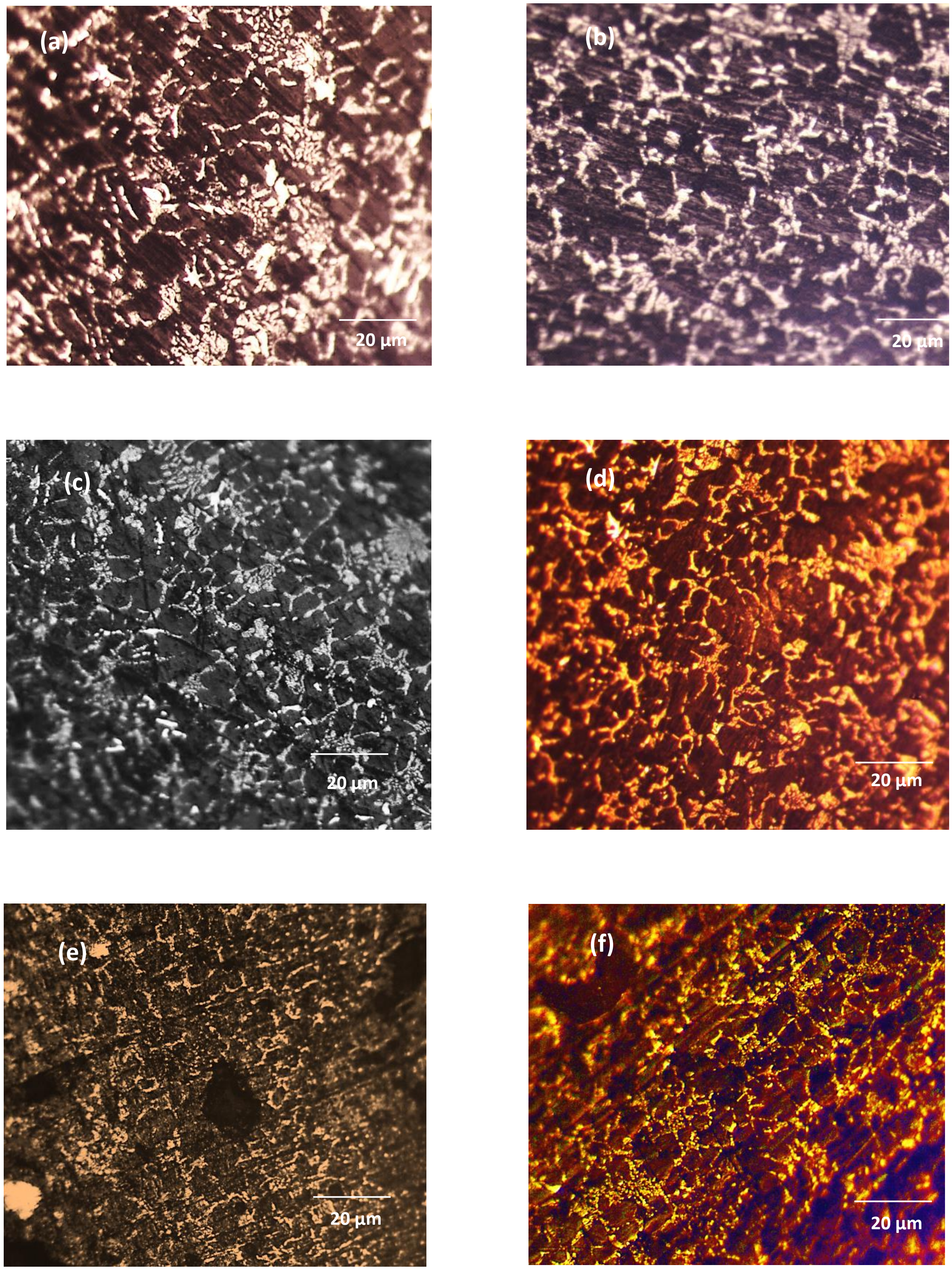
8.1 Material Characterization

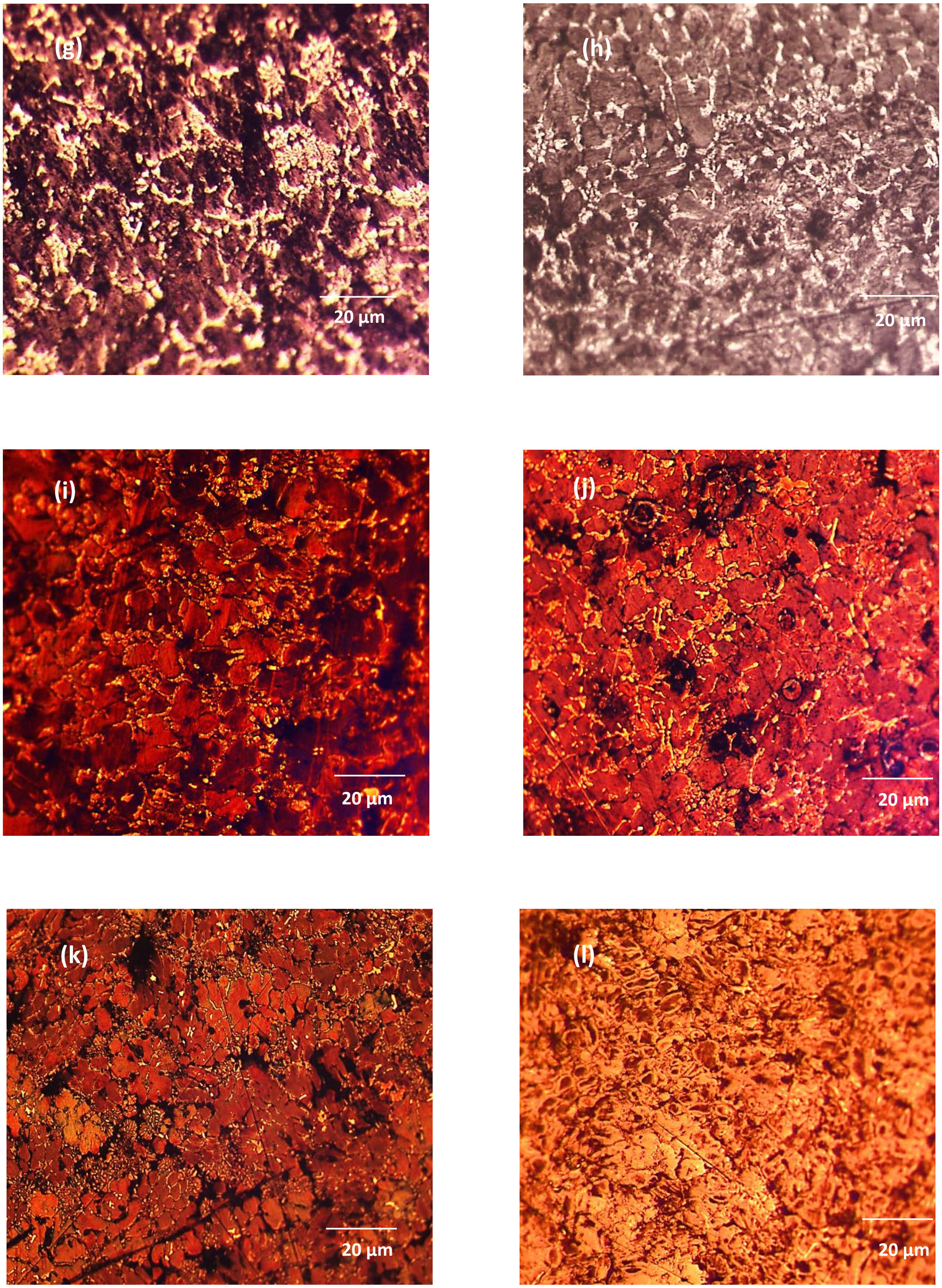
Different material characterization techniques have been utilized for testing the as cast samples material's integrity and compare them for examining the material properties achieved after each gravity casting and spin casting process. Different types of Material Testing Techniques have been utilized like hardness testing, tensile strength measurements, optical and Scanning Electron Microscopy and Surface Analysis, etc. Surface Analysis of the cast parts have been done using the digital profilometer in order to find out the surface roughness profiles for testing the surface morphology of cast products achieve from each type of molding method. Moreover, the Material Characterization techniques helped to provide extensive data for the material's properties and integrity in terms of product quality by examining the microstructure and porosity within. The results from each type of techniques have been compared and illustrated in detail in respective sections.

8.2 Scanning Electron Microscopy and Optical Microscopy

Metallographic Analysis of casted TEKALOY ZA-I samples was performed using Optical microscope and Scanning Electron Microscope (SEM) in order to examine possible variations in the grains size and shape and alloy distribution in the specimens from all casting procedures performed. The microstructural examination method has been utilized in order to fully identify the possible structural changes in each category of samples. The characterization of the phases has been done under optical microscope for specimens under different magnification levels to examine the grain size and morphology of the phases. The samples were prepared as specified by ASTM E3-11 specifications for Zinc and Zinc Alloys, and then etched with 5% hydrochloric solution in ethanol for 3 seconds then rinsed and at last, in Chromic acid solution (50 g Cr_2O_3; 4gNa_2SO_4 in100 ml water) for 10 seconds at room temperature.

The average sizes of the grains in the microstructure of each sample casted at different rotational speeds have been analyzed by measuring the average diameter of equiaxed grains as per standard procedure ASTM E 112-96. For determining the grain size of the specimens, each TEKALOY ZA-I sample was allocated into several equal portions. Then the average diameters of the equiaxed grains were measured in each portion of 15 mm approximately. Grain size is the characteristic of change in the solidification pattern of molten metal during casting. Hence reveals the alterations in the microstructural morphology that facilitate to study the grain size effect on corrosion behavior of TEKALOY ZA-I, which have been reported in the separate studies. The optical micrographs of the TEKALOY ZA-1 castings have been illustrated in the figure 57 (a-n).


(a)
20 µm
(b)
20 µm
(c)
20 µm
(d)
20 µm
(e)
20 µm
(f)
20 µm


(g)
20 µm
(h)
20 µm
(i)
20 µm
(j)
20 µm
(k)
20 µm
(l)
20 µm

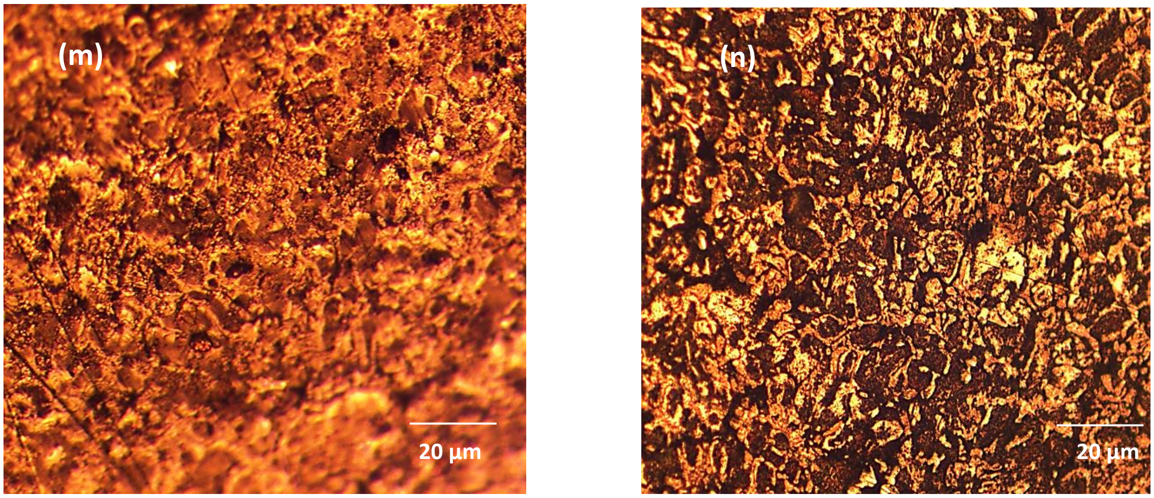
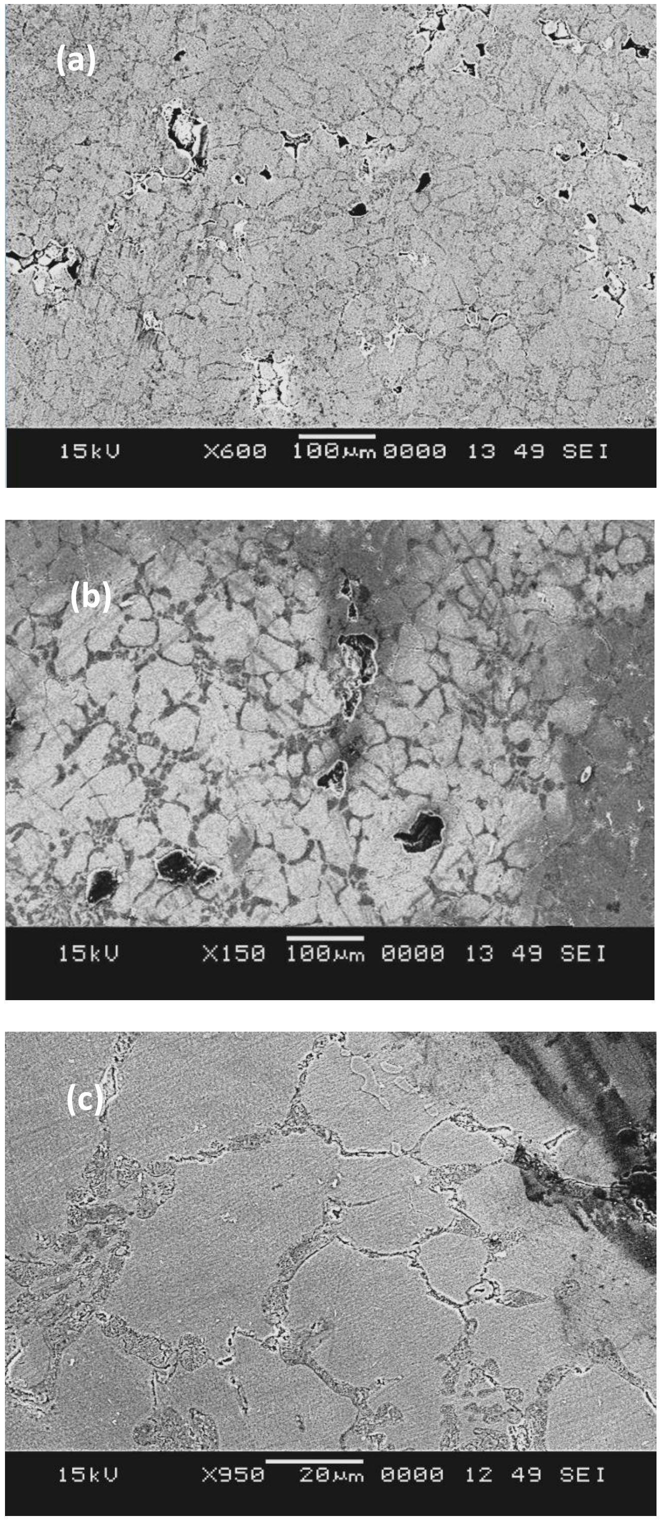


Figure 57 Optical Micrographs of Spin Cast Samples (a-f), Ceramic Mold Cast Samples (g, h), Plaster Mold Cast (i-k), Sand Cast Samples (l-n)

TEKALOY ZA-I alloy series is basically the quaternary alloys of Zinc consist of mainly Zinc, Aluminium, Magnesium and Copper, and lies in the category of hypoeutectic alloy due to presence of Aluminum less than 6% wt in the zinc matrix. The microstructure of the matrix mainly consists of coarse crystalline grains which include the primary phase η (it is rich in Zn content) and this primary phase is surrounded by binary eutectic matrix of ε and η phases, ε is the metastable phase forms by the addition of copper. Copper and Magnesium that are added to the binary alloy system of Zinc and aluminum impede the eutectoid transformation. Impurities like cadmium, lead and tin imposed deleterious effect in corrosion as can be seen in (Figure 58e & 58f). Typical micrographs of the TEKALOY ZA-I alloy specimens under SEM after chemically etched are presented in (Figure 58 & 60).


(a)
15kV X600 100µm 0000 13 49 SEI
(b)
15kV X150 100µm 0000 13 49 SEI
(c)
15kV X950 20µm 0000 12 49 SEI

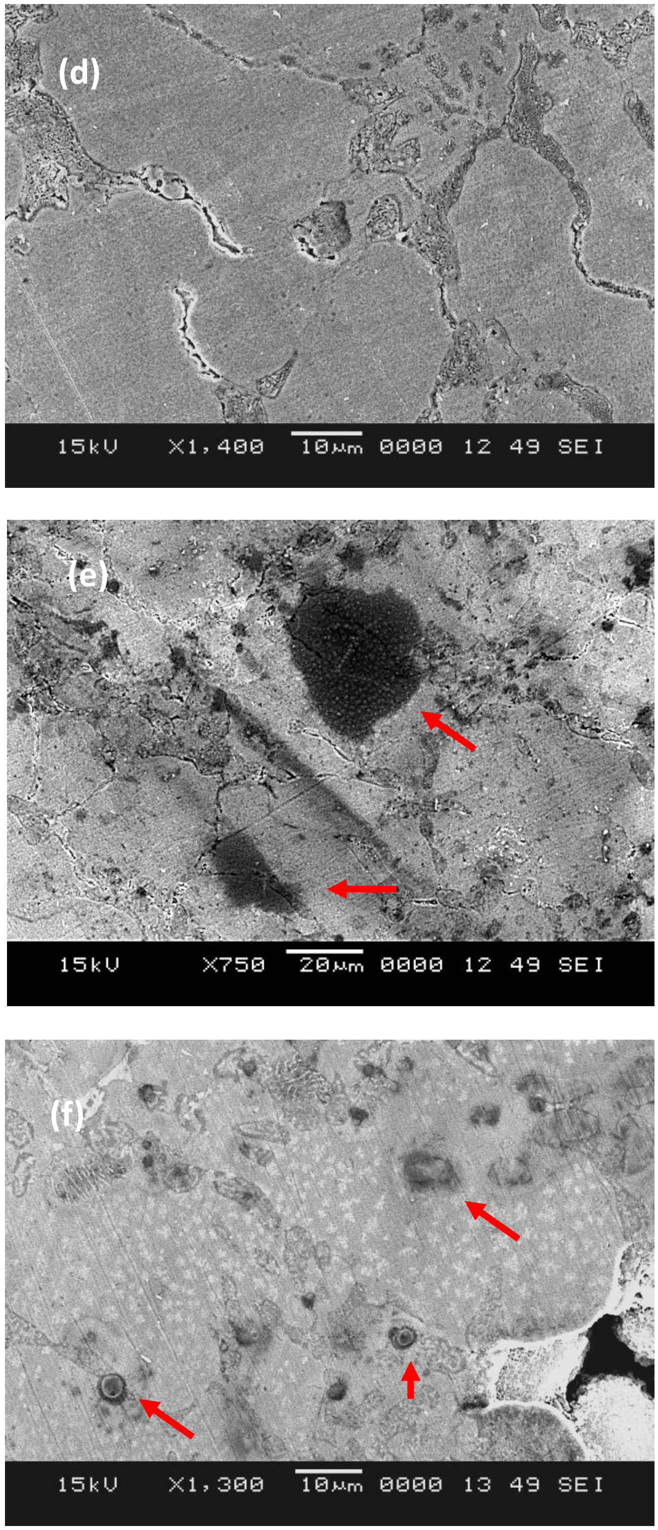


Figure 58: SEM Micrographs of TEKALOY ZA-I illustrating (a) sand cast sample, (b) Plaster Mold Cast sample, (c, d) [ε, η and T'] phases in the matrix of Ceramic Mold Cast samples, (e, f) segregated impurities in the matrix of Spin Cast samples.

Copper is found to decrease the tensile strength and impact resistance of TEKALOY ZA-I alloy due to formation of zinc- and copper-rich ε and T' phases formed within dendritic regions in the Microstructure (Figure 58c, 58d & 58f) and the copper rich intermetallic phase $CuZn_4$ is brittle and harder in nature than the zinc rich matrix, which increases the tendency of this alloy to crack along the grain boundaries of the TEKALOY ZA-I alloys. While the magnesium forms a magnesium rich phase that changes the overall morphology of the primary dendrites in the matrix. In the SEM micrographs all phases are illustrated and can be observed in (Figure 58c, 58d & 58f).

It is shown in companion study that the average grain size in the Zn–Al matrix is reduced as a function of the mold rotational speed for spin casting samples except some samples that demonstrated little variation from the trend. The sizes and morphology of the grains casted with different molding methods are variedly distributed in between 15 microns to 25 microns.

8.3 Corrosion Behavior of Cast Samples

In some casted samples the porosity in the microstructure is dominant (Figure 60a), dispersed along the grain boundaries due to incomplete fusion of the corresponding dendritic grains (Figure 60b & 60c). These porosities in the granular structure can act as a potential corrosion sites on opposing faces due to metallurgical disparities in the hardness, morphology, thermal state, and compositions (Figure 60c-60f). Also it has been discussed before the presence of the impurities like cadmium, lead and tin at the grain boundaries and at these porosity sites are very favorable and potential for the corrosion to occur. The grain dendritic size reduced by increasing the rotational speeds resulted in greater amount of grain boundaries and irregular cooling leaded to large number of porosities- hence the corrosion sites. These increased areas of porosity and corrosion sites gave rise to the corrosion rate of the TEKALOY ZA-I alloy when casted at the higher speeds or cooling rates. Figure 59 shows the typical polarization curves of the TEKALOY ZA-I achieved as a result of Potentiodynamic polarization corrosion test of the TEKALOY ZA-I sample.

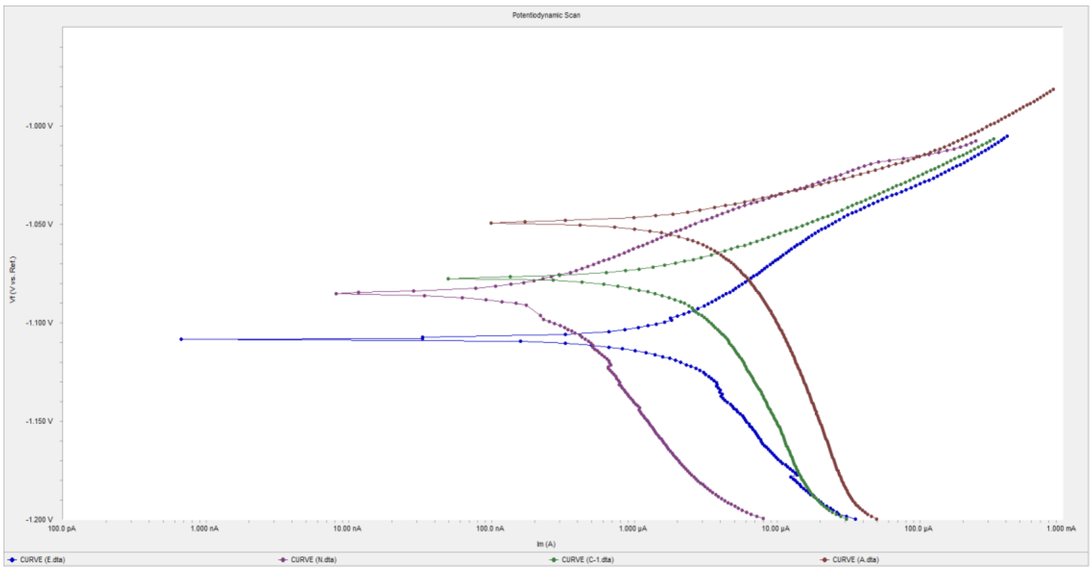
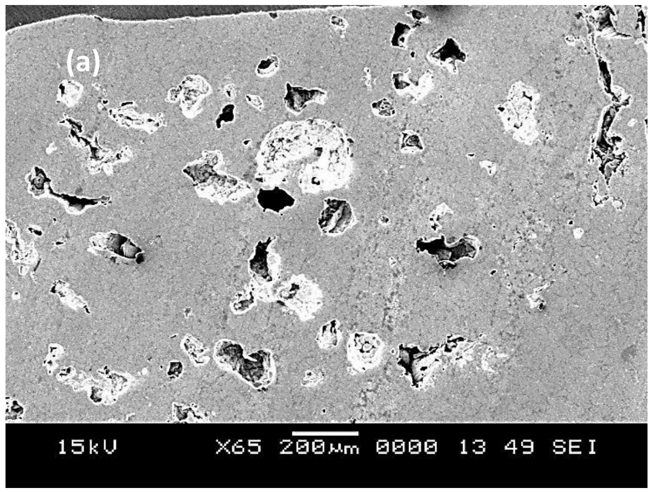
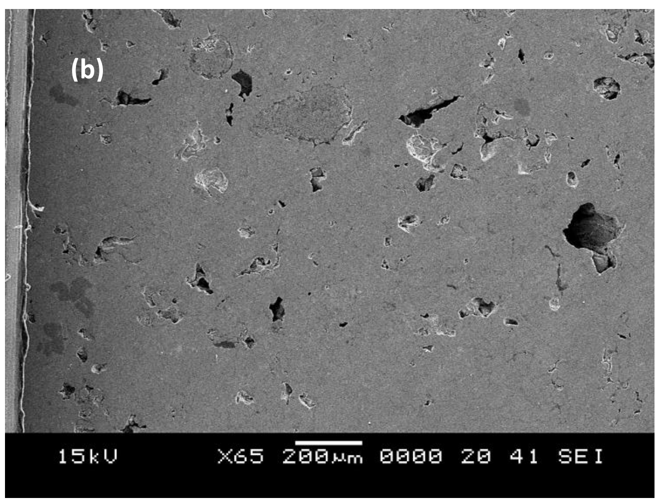
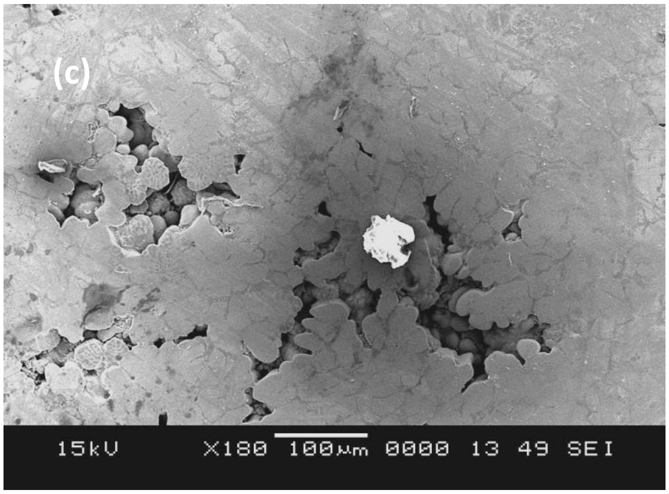


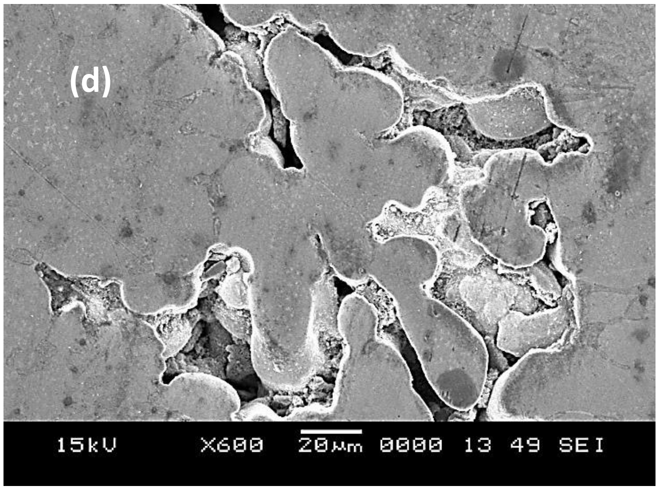
Figure 59 shows the typical polarization curves of the TEKALOY ZA-I achieved as a result of Potentiodynamic polarization corrosion test

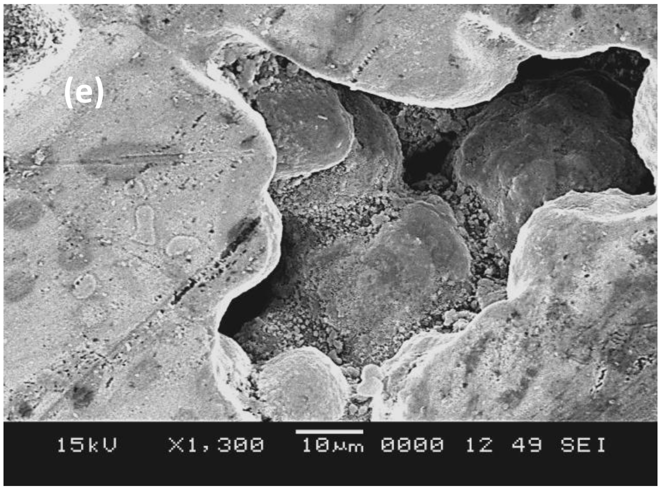
This phenomenon of increase in corrosion rate with the porosity content may not be followed by all the alloys and hence cannot be generalized for all the metallic alloys. As there are several parameters and operating procedures upon which the corrosion is interdependent. So all these parameters will have to be optimized to get sound casting with optimized physical, mechanical and have good corrosion life. The following Figure 60 (a-g) shows the porosity defects of TEKALOY ZA-1 samples under SEM. The average porosity content in Standard, sand cast, plaster mold cast, and 3D printed ceramic mold cast parts are found to be 13.13%, 6.48%, 6.02%, and 11.18% respectively, while for the spin cast samples the porosity varies with in the range of 2% to 14% depending on the rotational speed, mold spinning time and pouring temperature of pouring metal.

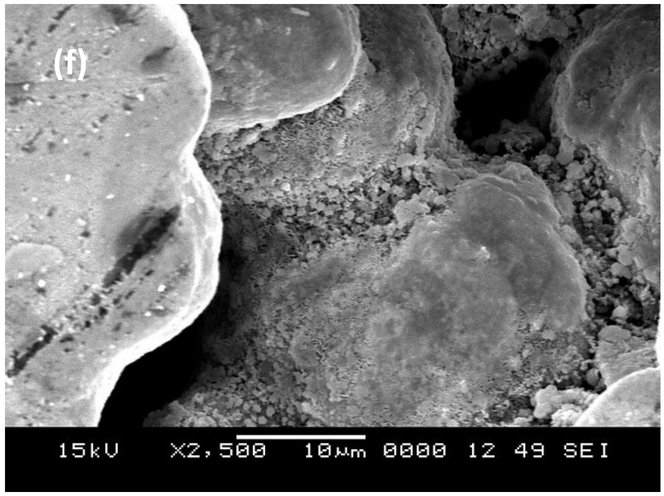





(c)
15kV X180 100μm 0000 13 49 SEI


(d)
15kV X600 20μm 0000 13 49 SEI


(e)
15kV X1,300 10μm 0000 12 49 SEI



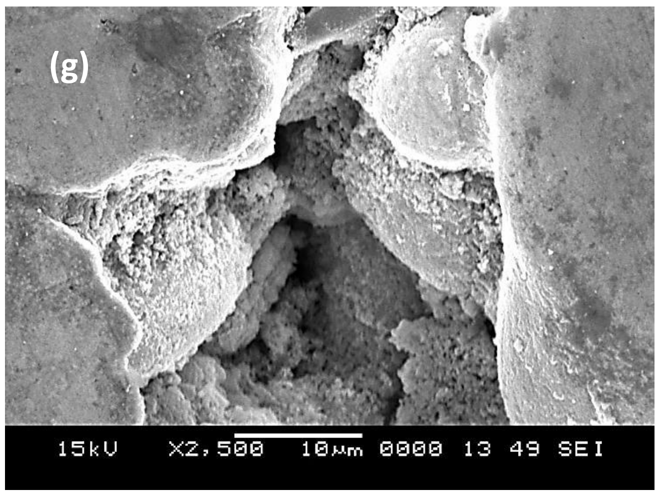


Figure 60(a-g): SEM Micrographs illustrating (a, b) highly porous casting structure, (c, d) incomplete fusion of grain boundaries, (e -g) porosity in depth-possible corrosion sites in Spin Cast TEKALOY ZA-1

8.4 Hardness Measurements

The Hardness of all the samples were then checked in order to get an idea of the effect of different rotation speeds, spinning time and the pressure on the hardness reading of the TEKALOY alloy samples. The hardness test was carried out on Brinell Hardness Tester in accordance to ASTM standard E10-12 and the Micro Vickers Hardness Tester using the diamond indenter and 100 gf. For the spin cast samples, it has been observed that a hardness values increased at corresponding higher mold rotational velocities. This analogous trend has been followed throughout the spinning time range by each combination of casted test samples 1- 4 (30 seconds), 5-8 (40 seconds), 9-12 (50 seconds) and 13-16 (60 seconds).

Longer rotation time and higher spinning mold speed tend to increase the cooling effect in the molten metal facilitates the formation of the smaller grain size and hence more grain boundaries are formed at the microstructure of the TEKALOY alloy during spin casting. This increase in the number of the grain boundaries, suppressed grain growth and faster cooling effect are the favorable characteristics for the increment in the hardness values of the metal. This behavior has been observed in Figure 61, in which the hardness values increment is noticeable for increasing rotational speeds irrespective of the test mold spinning times.

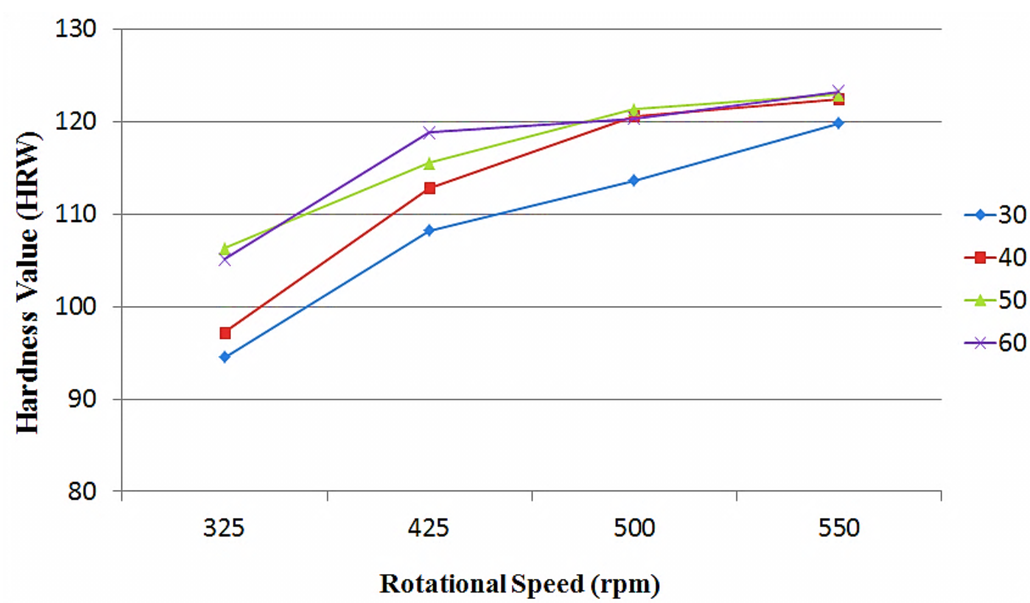


Figure 61 Trend illustrating direct contribution of the rotational speed and time on the hardness values of TEKALOY ZA-1

As for the gravity casting methods, the sand mold cast and plaster mold cast parts showed the higher hardness values than the ceramic mold cast and spin cast parts. While the standard as received parts possess the average hardness values. The hardness was measured along the cross section at four different places (a,b,c,d) as shown in Figure 62.

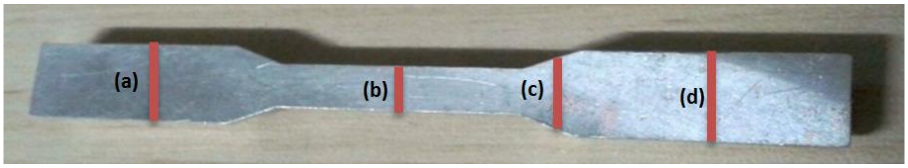


Figure 62 Sampling Plan for the Hardness Tests of TEKALOY Castings

The comparative hardness vs. tensile strength graphs Figure 63 shows the increasing trend of hardness with the tensile strength for each type of casting, representing the spin cast samples having the higher tensile strength but lower values of Hardness while the sand cast and plaster mold cast parts possess the highest hardness values than the ceramic mold cast and standard as received samples.

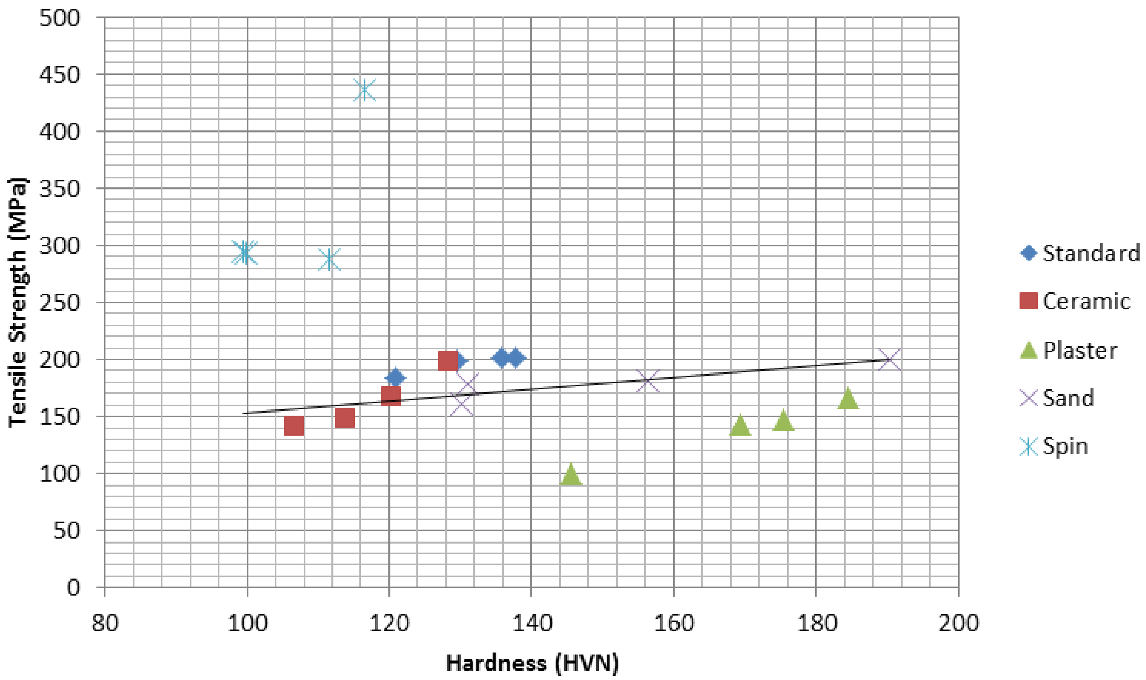


Figure 63 Comparative Hardness VS Tensile strength curves for the gravity casting methods vs. spin casting

8.5 Tensile Strength

For analyzing the mechanical strength of the gravity cast and the spin cast TEKALOY ZA-1 samples the tensile strength tests of several samples have been carried out. The Instron Universal Testing Machine has been utilized for this purpose with applying the Standard Operating Procedures.

TEKALOY ZA-1 castings found to have brittle nature of fracture during the tensile testing as they have shown little amount of plastic deformation with minimal elongation Figure 64 shows the brittle cleavage fracture almost perpendicular to the applied tensile stress.

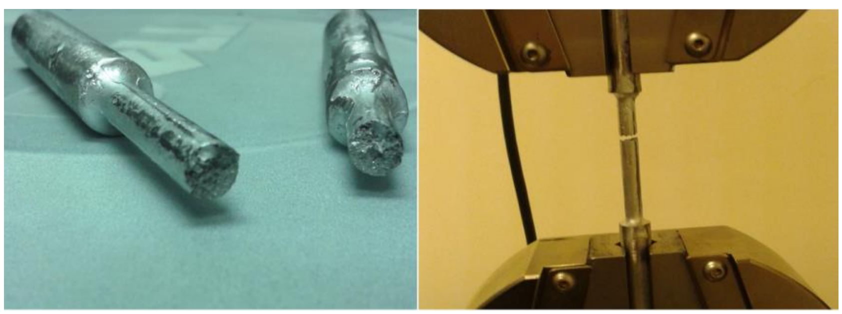


Figure 64 Brittle Fracture in the Spin Cast Specimen without necking during the tensile test

Figure 65 illustrates the comparative tensile strength results in the form of stress-strain curves, in which the sand casting parts shows the almost similar Ultimate Tensile Stress and strain values as of the standard as received machined part from the ingot. While the plaster mold cast part shows lower UTS values than the 3D print ceramic mold cast part, possibly due to the faster cooling effect due to presence of pores in the ceramic mold. The trend for Ultimate Tensile Strength is $\mathbf{TS_{SP} > TS_{SN} > TS_{ST} > TS_{CR} > TS_{PL}}$.

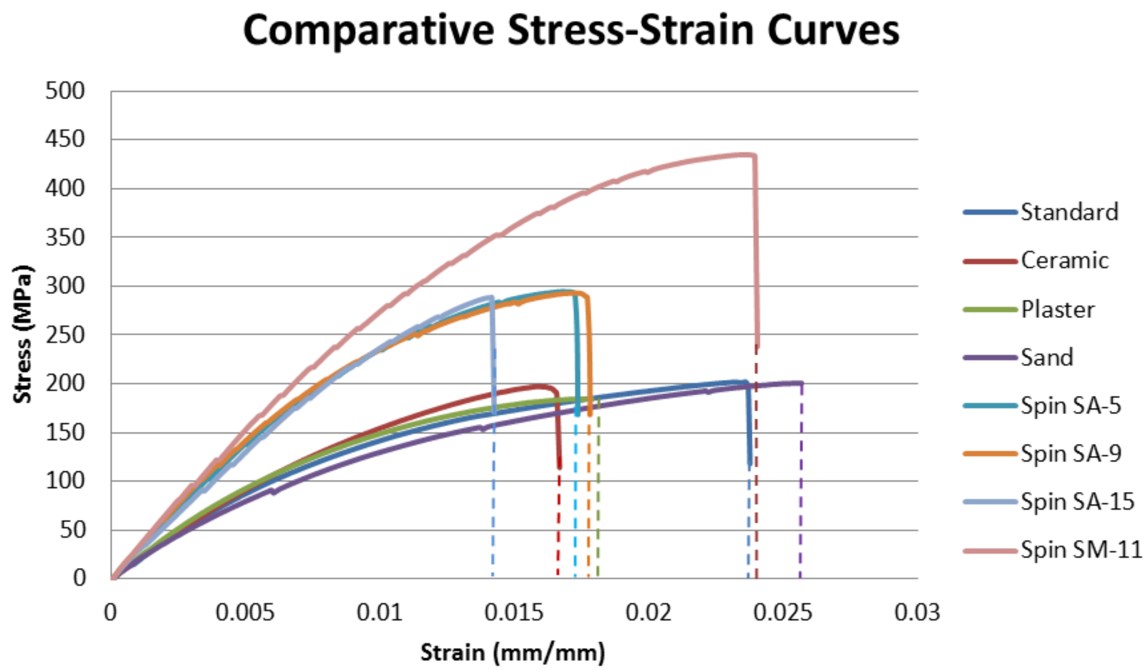


Figure 65 Comparative tensile stress-strain curves for the gravity casting methods vs. spin casting.

8.6 Dimensional Precision

The precision level of the parts manufactured with the spin casting in a rubber mold is comparable to the die casting and investment casting processes, but not as good as that of the die casting or ceramic investment mold casting due to the poor thermal properties of the mold material including low latent heat, thermal conduction, greater thermal expansion and complex combination effect of process parameters that influences the overall dimensions of the final casting and this deviation in the dimensions keep on increasing with the number of cycles and reusing of the same mold. While for the sand cast parts the dimensional precision is found to be closer to that of the standard theoretical dimensions followed by plaster mold and 3D printed ceramic mold cast parts.

The dimensional Accuracy has been assessed by measuring the major dimensions of the cast parts and compared them with the theoretical values.

8.7 Surface Morphology and Integrity

Surface finish has been identified by using digital profilometer to get the surface roughness data. Visibly the Plaster cast, spin cast and sand cast parts showed better surface finish then the ceramic mold cast parts which contains surface dimples on the samples. While plaster mold cast and spin cast parts found to have smooth surface with little surface defects Figure 66. The surface roughness values are measured by using Stylus profilometer, the R_s values are found to be 8.16µm, 5.86µm, 4.73µm, 12.42µm, 16.76µm for Spin cast, Plaster mold cast, standard machined, sand cast and 3D ceramic mold cast samples respectively.

Figure 66 Surface Finish of casted samples from left to right (sand cast, spin cast, machined standard sample, plaster mold cast, 3D printed ceramic mold cast)

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The novelty and the main contributions of this research study can be summarized in following points:

i. Feasibility assessment for casting the **TEKALOY ZA-I** (a die-casting Zinc alloy) via gravity casting route.

ii. Utilization of Advanced Simulation Tool for mold design optimization of 3D Z-printed Ceramic Mold Casting (Direct Metal Casting).

iii. Comparative quality analysis of spin casting process with the other conventional gravity casting methods.

iv. Study of Parametric relationships amongst the process parameters of spin casting for the product quality optimization.

v. Development of Predictive models for Porosity and Tensile strength that can be utilized in future for generating spin casting simulation software.

CONCLUSIONS

Advanced Simulation Tool showed considerable savings of time and resources by providing intelligent solutions through soft optimization of casting quality without tedious trial and error methods. 3D Printing Direct Metal Casting could be a better replacement of troublesome pattern making, mold making, and complex molding operations but low thermal conduction, varying mold ceramic powder size and binder burn out limits its use. Plaster mold cast parts demonstrated highest surface quality but the mold needs proper curing time before pouring of the metal to minimize casting defects.

Comparative analysis of the spin casting and other gravity casting methods have been carried out in order to have comprehensive qualitative mechanical and metallurgical data for the cast products. Qualitative analysis of the cast products showed varying responses in each type of material characterization test. For hardness test, sand cast parts possess the highest hardness values than other gravity casting methods and spin casting. Spin cast samples demonstrated the highest ultimate tensile strength among other castings.

As for the dimensional accuracy, spin cast samples are found to be the most accurate followed by the sand cast; plaster mold cast and the 3D Z-printed ceramic mold cast parts. In case of surface finish; plaster mold cast parts and sand cast parts showed the highest surface finish followed by spin cast parts and 3D Z-print ceramic mold cast parts that displayed the lowest surface finish and needed a greater amount of casting finishing operation.

Additional study on the corrosion behavior of TEKALOY ZA-I has been carried out. Spin cast parts prepared at higher revolution speeds and time found to have the highest corrosion rate in Epsom salt solution as compared to the other gravity casting methods measured by the Potentiodynamic Polarization method. Porosity and impurities in microstructures acted as the main corrosion sites; as observed under SEM and optical microscope. Also, stresses developed during the spin casting contribute to the stress corrosion cracking of TEKALOY castings.

Parametric analysis for exploring insights of the spin casting process with a detailed study of process capabilities and limitations have been carried out for defining the specific relationships between the process parameters through experimentation. Furthermore, two predictive models for the porosity and tensile strength have been developed for the quality optimization of spin cast products that will help the manufacturers to optimize the spin cast product quality for minimal defects if the models are incorporated in the development of a spin casting module in any simulation software.

RECOMMENDATIONS

In order to diversify the utilization of the spin casting process, modifications in the mold materials for high-temperature alloys casting needs further investigation. This can be achieved by introducing high-temperature resistant mold materials. 3D printed ceramic molds and runners can also be embedded in the mold as long as it is compatible with the dimensional constraints of the mold to increase the temperature limits of casting materials in the same silicon rubber molds.

Spin casting process can further be optimized by utilizing the CAD modeling and 3D printing techniques for making runner and gating system in order to have high dimensional accuracy and to avoid tedious job of manual preparation of the mold.

It is recommended to develop spin casting simulation software based on FVM, FDM and FEM methods instead of adopting troublesome trial and error methods in real time production facilities. The software will help to predict the casting properties, defects, and the final soundness right at the designing phase, well ahead before the real-time casting, which will save the overall production cost and lead time.

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