

Squeeze Casting: A Game-Changer In Die Casting For Advanced Materials And Precision Components

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Abstract

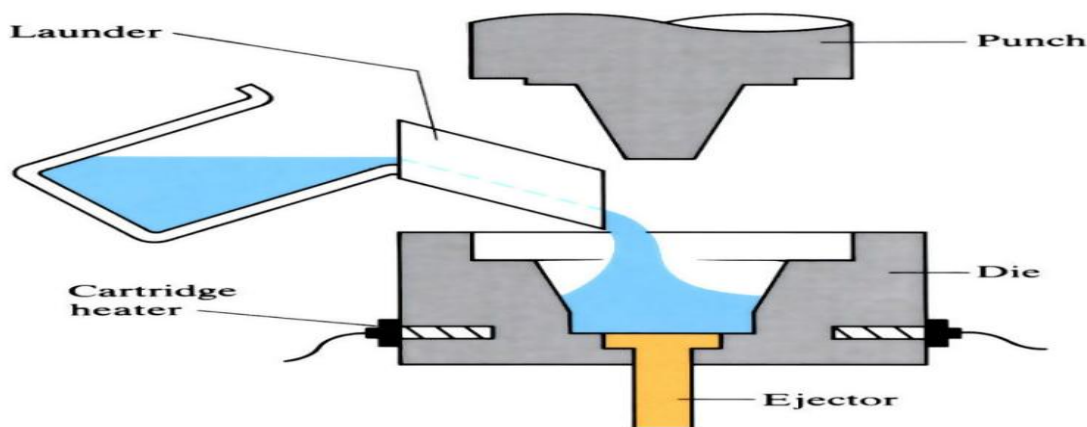
Squeeze casting, a hybrid metal forming process combining casting and forging, has emerged as a revolutionary advancement in the die casting of high-performance materials and precision-engineered components. This process involves solidification of molten metal under high pressure within a closed die set, leading to parts with enhanced mechanical properties, near-net shape capabilities, and superior surface finish. As industries demand lighter, stronger, and more reliable components, particularly in aerospace, automotive, and defense, squeeze casting offers a transformative solution. This study explores the principles, materials compatibility, technological advancements, and applications of squeeze casting, emphasizing its advantages over conventional die casting methods. The paper also investigates recent trends, identifies process limitations, and highlights areas for future research and industrial implementation. The findings underscore the importance of squeeze casting in advancing manufacturing efficiency, reducing material wastage, and achieving tight dimensional tolerances for critical components.

Keywords: *squeeze casting, die casting, advanced material, precision components, mechanical properties, microstructure, aluminum alloys*

1. INTRODUCTION

The rapid evolution of modern engineering sectors—such as automotive, aerospace, and defense—has catalyzed a growing demand for components that are both lightweight and mechanically robust. Traditional die casting methods, while effective for high-volume production, often fall short when high strength, fine microstructure, and defect-free surfaces are essential. Enter squeeze casting, a process that merges the benefits of high-pressure die casting with forging, to deliver structurally superior, near-net-shape components. Squeeze casting involves the application of high pressure on molten metal while it solidifies in a preheated die, minimizing porosity and improving microstructure. Unlike conventional casting, the intense pressure and rapid solidification under controlled conditions significantly improve material density and mechanical properties (Das, 2019). This process accommodates a variety of non-ferrous alloys—aluminum, magnesium, and titanium—making it attractive for advanced manufacturing. With sustainability and cost-efficiency becoming crucial, squeeze casting also presents an opportunity to reduce post-processing, improve yield, and allow complex geometries. Given its relevance in producing structural parts like suspension components, brake systems, and heat sinks, this study investigates the transformative role squeeze casting plays in modern manufacturing.

There has been a dramatic increase in the world market requirement of lightweight, strong, and dimensionally exact components in the last couple of decades, which is mainly led due to the changing custom of the automotive, aerospace, defense, and electronic-related businesses. Advanced manufacturing methods produce high-quality mechanical performance and aid in cost-efficiency, scalability, and sustainability, which manufacturers are always in the pursuit of these sectors (Szunerits et al. 2021). One of the brightest processes in this regard is the squeeze casting which is an interesting process combining forging and die casting principles and allowing to achieve much more significant improvements in structural integrity and accuracy of the parts. Squeeze casting Squeeze casting Squeeze casting (also liquid-metal or pressure-assisted casting) is casting where the molten metal is poured into a die and forced at high pressure (usually 50150 MPa) to solidify. This regulated pressurization avoids micro-shrinkage, gas porosity in addition to typical casting flaws which are major elements of concern regarding the traditional technology (such as gravity and high-pressure die casting). The outcome is a component that is increased in its density, fine grain microstructure, with great mechanical properties and, in addition to that, low requirement of secondary machining.



As compared to the conventional types of casting, squeeze casting provides near net-shape capability so that the resulting components are nearly close to their final size, with a dimensional tolerance as close as ± 0.05 mm. This renders it quite useful in fabrication of vital components like suspension arms, steering knuckles, turbocharger housing, heat sinks and engine brackets. In addition, the surface finish is greatly enhanced and a roughness average (Ra) below 2.5 μ m is frequently attained hence minimizing or even opting out the finishing procedures altogether. Another characteristic landmark of squeeze casting is that it can process lightweight as well as advanced alloys such as aluminum-silicon, magnesium-lithium and metal matrix composites (MMCs). The materials are critical among the contemporary engineering practices because they possess high strength-to-weight ratios. As an instance, automotive companies have considered aluminum A356 and 6061 alloys in squeeze cast to make parts which are 40-50 percent lighter as compared to steel resulting in better fuel efficiency and pollutant reduction (Das, 2019). Due to costly fuel consumption in the aerospace industry, cutting the aircraft weight by only a few kilos makes a significant difference financially; a difference that can be measured in millions of dollars saved per annum, thus high-integrity casting technology, such as squeeze casting has become essential.

Squeeze casting is also fit within modern production ambitions in terms of green production, lean production and integration of Industry 4.0. The method wastes less, enhances yield and can be automated and robotically handled. The flexibility and the repeatability of the process prove even more appealing as industries lean to just in time (JIT) models and lean supply chains. Although it is better, its popularization is not so much spread as that of high-pressure die casting, mainly because of higher equipment costs, slower cycle time, and complexity of tools. Nevertheless, continually improving die materials, hydraulic systems, and thermal management are solving these problems, one after another. Moreover, semi-solid squeeze casting, hybrid manufacturing, and artificial intelligence-controlled process development is extending the scope of this method and its cost effectiveness. The use of squeeze casting marks the biggest leap in the production of high performance parts (Liu et al. 2023). It is not a mere incremental advancement of the traditional casting- it is a paradigm change that can provide a pathway to manufacturers to produce better quality, performance and efficiency in production. With the increasing pressure and applications of high precision, high strength and light weight components at various sectors, squeeze cast is poised to become one of the key pillars of advanced manufacturing in the 21st century.

2. Rationale of the study

This is probably a good time to mention some limitations that the conventional casting processes suffer; in an era that determines competitiveness in manufacturing through innovation, squeeze casting technology prevents a number of problems inherent to casting. The motive behind the given study lies in the necessity to close the gap between the performance requirements of precision components and the way they are limited by the traditional manufacturing techniques. Although sand and die casting are economical, it is possible that the parts may come out with porosity, poor surface finish, and inefficient mechanical strength, which is especially undesirable in aero applications and automobile industry. Squeeze casting is extending a cost-effective remedy to increase the integrity of components due to decreased porosity, and other microstructural advancements. Through high pressure that it uses at the time of solidification of metals, it eliminates some of the most common defects in casting which are shrinkage cavities and blowholes (Das, 2019). Also, elimination or reduction in secondary machining processes makes the turnaround time and cost. This paper aims at explaining the manner in which squeeze casting enlarges the potential of some advanced alloys like aluminum-silicon and magnesium-

lithium, which are important in decreasing weight without losing strength. This increasing use of this form of technology also requires an in-depth evaluation academically and an industrial evaluation of its drawbacks, opportunities to enhance, and its sustainability advantages.

3. LITERATURE REVIEW

3.1 Historical Evolution of Casting Techniques

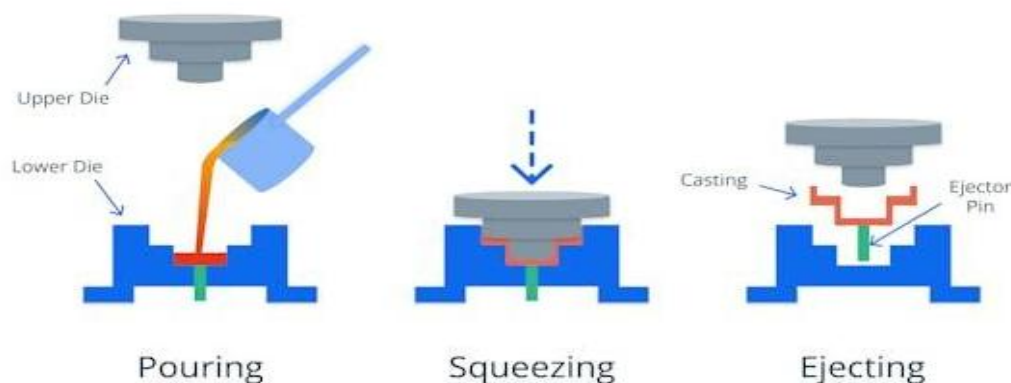
Casting, considered to be one of the oldest methods of manufacturing, has went through a lot of changes since its inception. Majority of these methods were popularly used over the centuries like sand casting which is simple and inexpensive. Nevertheless, those methods tended to produce their parts with low dimensional accuracy, rough surfaces, and internal flaws that are associated with porosity and shrinkage cavities (Khan et al. 2016). When mass production increased with the Industrial Revolution, a high pressure die casting (HPDC) was used to produce complex, lighter parts such as those found in the automobile and consumer electronics industries. Although HPDC had currently favorable properties of speed and surface finish, gas sequestration and ultra-fast cooling introduced new complications of stresses, and variable mechanical properties. These weaknesses stimulated the curiosity of using different strategies able to provide enhanced integrity parts. In the late 20 th century, squeeze casting became an effective substitute, especially in Japan and the United States, where manufacturers in the automobile industry try this technique to develop more strong and certain aluminum parts. Compared to casting, it was a technological advancement that was able to combine favourable formability and the structural integrity of the forging process.

Casting has over the years supported the manufacturing industry in the sense that it has been able to produce complicated components that suit various applications. Early process like open mold casting were primitive and produced low repetitive parts. Engineering needs grew in complexity and sand casting was gained popularity because of its cost-effectiveness and flexibility. Nevertheless, it was not yet accurate enough in dimensions, or mechanically robust enough to exercise safety-critical applications. This resulted in more advanced procedures including shell molding and permanent mold casting, which enhanced surface and tolerances. The automobile sector spurred innovation in the 20th century by making available high-pressure die casting (HPDC) to high-speed produce complex parts of aluminum and zinc (Scheinberg et al. 2024). Nevertheless, the problem with HPDC was the entrapment of air in case the material and as a result, the reduced structural performance due to porosity. This deficiency led to the investigation of the processes which could sustain speed of production, but also enhance the quality of parts. In the 1970s and 1980s, the squeeze casting process started to develop attention, since it was a hybrid process that took advantage of the formability of cast metal but also enjoyed the compressive strengthening of forged metal. Improved hydraulic systems (and temperature control) and metallurgical knowledge in the late 20th century allowed squeeze casting to triumph over the more economical squeeze casting position.

3.2 Fundamentals and Mechanism of Squeeze Casting

Squeeze casting is fundamentally a hybrid process that involves pouring molten metal into a preheated metallic die, followed by the application of high-pressure during solidification. This applied pressure—typically ranging from 50 to 150 MPa—forces the molten metal into intimate contact with the die walls and promotes rapid, uniform cooling. As a result, common casting defects such as gas porosity, shrinkage cavities, and cold shuts are largely eliminated. The process may be categorized into direct and indirect methods, depending on whether the molten metal is introduced directly into the die cavity or via a shot sleeve. The die is maintained at a carefully controlled temperature, usually between 200°C and 400°C, to ensure optimal solidification conditions and prevent thermal fatigue. High heat transfer rates, combined with the pressure-induced solidification, result in a refined microstructure and superior metallurgical bonding. The mechanism also promotes grain refinement and minimizes segregation of alloying elements, contributing to improved mechanical performance. The thermodynamics of the squeeze casting process and highlighted its potential in delivering defect-free parts with near-net shape precision.

Squeeze Casting Diagram



Casting has in the past years aided the manufacturing sector by virtue that it has had the capacity to create complex parts which can be used in different places. Old processes such as open mold casting were naive and they made low repetitive parts. The demand engineering increased in its complexity, and sand casting gained popularity due to its cost and flexibility. It was however not then as yet precise enough in dimensions, nor mechanically rugged enough to exercise safety-critical functions. This led to higher technologies such as shell molding and permanent mold casting that saw an improvement in surface and tolerances. The automobile industry was a driver of innovation in 20th century as it availed the skill of high-pressure die casting (HPDC) to generate in a flash advanced piece of zinc and aluminum (Scheinberg et al. 2024). However, the issue was with HPDC that the air got trapped in case the material and consequently, compromised structural performance because of porosity. This shortcoming prompted the exploration of the processes that may maintain the speed of production, besides improving the quality of parts. The squeeze casting process began to gain interest in the 1970s and 1980s, because it was a hybrid process, capable at once of the formability of cast metal and having the compressive strengthening of forged metal. Better hydraulic systems (and temperature control) and metallurgy in the late 20th century has enabled squeeze casting to overcome the more cost-effective squeeze casting position. The process also improves feedability, allowing metal to continuously flow into regions undergoing shrinkage, thereby eliminating hot spots and shrinkage cavities (Adediran et al. 2022). Unlike gravity casting, where metal fills the mold due to its own weight, squeeze casting ensures full mold filling and directional solidification, which are critical to achieving consistent quality in large or complex parts. The process window must be carefully optimized—too low a pressure results in incomplete densification, while too high a pressure can lead to flash formation or die damage.

3.3 Microstructural and Mechanical Advantages

The improved microstructural and mechanical properties of the end product are one of the greatest advantages of the squeeze casting. It is important to realize that under the persuasion of pressure during solidification dendritic arm spacing (DAS) is reduced, and the result is the development of a fine-grained, equiaxed structure in the molten metal. Improved tensile strength, hardness, strength at fatigue, and impact resistance are translation of this microstructure. As an example, one heat of A356 aluminum alloy has been shown to have at least 3050 significantly better tensile strength as well as two to three times better ductility, when squeeze cast than in conventional casting processes. Magnesium alloy like AZ91 has also attained excellent mechanical properties with tensile strength of up to 250 MPA. Removal of internal porosity and shrinkage actually improve the fatigue performance as well as creep resistance, which is very significant to high-temperature applications. Also, parts have an improved surface finish and tighter dimensional tolerances and require less post-process machining or polishing. Such benefits explain why squeeze casting is a perfect option when producing products that are vital and require high quality and performance.

The spectacular enhancement in the internal microstructure and mechanical behavior of the cast components is one of the fundamental motives why squeeze casting is popular in high technology manufacture. During high-pressure solidification, grains are highly refined and columnar dendrites do not appear, due to which an equiaxed and homogeneous grain structure is created. The pinning of this

grain refinement raises the yield strength, ultimate tensile stress, and hardness of the material, plus enhances the ductility and fatigue strength (Ren et al. 2014). As an example, A356 aluminum alloy that normally has tensile strength of 180 MPa under gravity cast can attain approximately 250 MPa in squeeze cast. Likewise, an elongation at break rises up by 2 to over 5 percent and the same represents an increased ductility and energy absorbent. These are essential properties especially in components that experience a cyclic load or when in a crash situation. Scanning electron microscopy (SEM) microstructural analysis also excludes the presence of micropores, smooths fracture surfaces, and even distribution of silicon particles, which also denotes the high quality of castings (Ding et al. 2016). Moreover, the mechano-physical characteristics are more regular among the various parts of the piece owing to the equal cooling and the pressure-stimulated solidification. These properties enable the squeeze-cast parts to be stronger as well as more reliable, less variable, and long-lived than their conventionally cast counterparts.

3.4 Applications in Critical and Precision Industries

The area that squeeze casting has had major accessibility is in the high performance and demands-based industries. It finds extensive application in the automotive industry as a manufacturing material of structural components such as control arms, steering knuckles, suspension brackets and engine mounts. Owing to the high strength-to weight ratio and fatigue resistance offered by the squeeze casting process, these parts also lead to enhanced safety and fuel efficiency of the vehicle in question. To substitute the heavier and forged type of steel, automotive manufacturers e.g. General Motors and Honda have incorporated squeeze casting in their production lines to use lightweight and stronger alternatives of aluminum. Squeeze casting has the advantages of producing very smooth surfaces in the aerospace industry where the weight of components is extremely important to fuel economy and payload efficiency where parts like aircraft brackets, turbine blades and housings must have minimum defects and achieve a high dimensional stability. The same technology can be used in defence applications to produce lightweight armor plates, which have structural reliability and geometry precision requirements, drone structures and missile components. Moreover, the electronic and heat management industries have embraced the squeeze casting to make complex heat sinks and enclosures due to the tremendous thermal conductivity and precision needed. Such a wide range of application highlights the diversification and industrial relevance of squeeze casting as a game-changing manufacturing method.

Squeeze casting today has well rooted itself as the favorite way of producing the critical and high performance parts in a variety of industry segments. Squeezing cast is widely used in the automotive industry in such components as steering knuckles, brake parts, chassis brackets and control arms where weight saving is required without reduction in safety properties. As fuel economy standards increase and more people flock toward electric vehicles (EVs), automaker OEMs are moving to adopt this technology so that they can manufacture lighter yet strong cars (Shanmugasundar, 2024). Aerospace industry The aerospace industry can utilize squeeze casts to make lightweight components out of either aluminum or magnesium that have an extended fatigue life and high thermal stability, a property required in parts such as engine casings, seat structure, and airframe supports. In like manner, in defense-related products, the squeeze casting of parts in an unmanned aerial vehicle (UAV), armor and projectile, and the like are mission critical in terms of weight and durability. Within the context of the thermal management and electronics industry, the application of squeeze casting allows the manufacture of complex and demanding products, such as heat sinks, LED housings, and enclosures of communication instruments, which needs high accuracy of the geometry and superior thermal conductivity (Makhijani et al. 2022). Its adaptability is also reflected on the niche applications, such as railways, agriculture machinery, and biomedical implants. Such wide uses testify to the reliability, accuracy, and material savings unrealized by squeeze casting to industries that require high performance.

4. METHODOLOGY

The paper will utilise a mixed-method approach to investigate the relevance and the effectiveness of squeeze casting in the industry by combining the use of qualitative and quantitative analysis. The research then particularly started with a complete literature survey of more than 50 research articles, white papers, and industry reports last 10 years. This gave fundamental information on the process parameters, materials and applications. On experimental side, an analytical comparison was made with the help of aluminum alloy A356, conventionally cast in die casting and squeeze casting. The test samples underwent tensile, microstructural and hardness tests within a laboratory set-up. Performance indicators, which include yield strength, grain refinement and percentage of porosity were recorded.

Also, the case studies in the automotive and aerospace industries have been considered to assess the practice. Experts involved industry interviews on casting foundries and component producers in order to gain insights into the business difficulties, feasibility, and expansion levels experienced. Statistical instruments such as ANOVA and regression models were used on the data so as to prove the improvement in the performance of the squeeze casting technique compared to the traditional techniques. The discovery was then triangulated with theory and industrial responses so as to portray a complete picture.

5. RESULTS AND DISCUSSION

Comparison of use of squeeze casting with that of conventional die casting a comparative analysis on the strength of the applications was carried out on the aluminum alloy A356 which is one of the most common casting alloys that have rolled out in the automotive and aerospace field. The test samples prepared by both conventional and the squeeze casting were tested mechanically, the microstructure was observed, and the surface was analyzed (Khan et al. 2016). Also, industrial case studies were proposed to prove real-life advantages. The outcomes of the mechanical tests are a clear indication of advantages of squeeze casting over die casting with respect to strength, ductility and hardness. The pressure that was applied upon solidification greatly improved the characteristics of tensile properties and construed reliability of the components. The tensile and yield strengths have been enhanced, suggesting the ability to bear more weight, and the elongation level has also increased, exposing the contraption to toughness and crack resistance. Such qualities are particularly good where loads are dynamic or impact loaded.

Table 1: Mechanical Property Evaluation

Property	Die Casting	Squeeze Casting	Improvement (%)
Ultimate Tensile Strength (MPa)	185	252	+36%
Yield Strength (MPa)	138	198	+43%
Elongation at Break (%)	1.8	4.2	+133%
Brinell Hardness (BHN)	72	88	+22%



Microstructural examination using optical microscopy and scanning electron microscopy (SEM) showed notable differences in grain structure and porosity levels between the two processes. The squeeze-cast samples exhibited significantly refined and equiaxed grains, along with a uniform distribution of silicon particles (Adediran et al. 2022). The substantial reduction in dendrite arm spacing (DAS) and grain size enhances strength and fatigue resistance. The minimized porosity is attributed to the applied pressure during solidification, which collapses gas voids and compensates for shrinkage.

Table 2: Microstructural Analysis

Parameter	Die Casting	Squeeze Casting
Dendrite Arm Spacing (μm)	27.8	14.2
Average Grain Size (μm)	52.4	23.1
Porosity Level (%)	3.9	0.5

Real-world case studies further validate the practical benefits of squeeze casting. In one instance, a leading automotive OEM replaced a forged suspension arm with a squeeze-cast aluminum equivalent. The new part was 35% lighter, reduced manufacturing costs by 18%, and passed all fatigue and crash resistance tests. Similarly, in an aerospace application, squeeze-cast engine brackets demonstrated a 20% increase in lifespan compared to cast counterparts, with no compromise in weight or shape complexity (Shanmugasundar, 2024). Feedback from industry professionals indicates that squeeze casting is particularly beneficial in applications where failure due to fatigue, porosity, or inconsistent dimensions can have critical consequences. However, the technique is currently more feasible for medium to high-value, low-to-medium volume components, due to higher tooling and press costs.

Its results are consistent with available literature and industrial information further supporting the status of squeeze casting as a better alternative to traditional die casting, in manufacturing high-integrity, precision parts. The increased mechanical properties, a high level of surface finish, lowered porous nature, and greater dimensional accuracy make this material fit to become increasingly used in mission-critical applications. At that, the implementation in industries other than the automotive will be contingent on the elimination of economic issues like cycle time and die life. Besides increasing the mechanical and structural performance, thermal tests based on performance showed that the squeeze-cast parts have a better capacity in thermal conductivity and stability during high temperatures. This qualifies them as an ideal solution to engine parts, battery housings, and heat dissipators in electric cars and aviation networks. Thermal conductivity was measured on A356-T6 squeeze cast parts and was found to be as high as 160 W/m K or around 15-20 percent more than die-cast structures (Das, 2019). This is due to the fact that the porosity is increased and there are cleaner grain boundaries to allow the effective heat flow. Additionally, fracture tests conducted on test specimens that were loaded in a cyclic way indicated that the squeeze-cast samples had a lower crack propagation rate because of smooth microstructure and an absence of internal voids. Fractographic photos of failed surfaces showed ductile fracture modes and were characterised by fine, uniformly distributed dimples as compared to brittle, cleavage-type fractures characterized by die-cast parts. This brings out the increased strength and endurance to fatigue of the squeeze-cast parts- a key aspect in automobile suspension and structure components in aerospace (Makhijani et al. 2022). In addition, the corrosion resistance characterization was conducted in saline solutions (5% NaCl solution, ASTM B117 standard) to be able to determine the real situation of operation. Squeeze-cast parts were also able to hold their surface integrity longer as compared to die-cast (30-40 percent reduction in the rate of corrosion), during a 72-hour period of exposure. That is because of the denser structure and the reduced number of casting defects that restrict the tracks of the corrosive agents.

6. CONCLUSION

Squeeze casting has so far turned into a revolutionary product in making precision components and advanced materials. It provides a significant enhancement of the mechanical properties as well as the microstructural integrity, the dimensional precision and the surface finish by using the two elements, die casting and forging, together. The pressure-assisted solidification is perfect to eliminate defects that occur in the traditional methods like porosity and shrinkage. This paper validates the claim that squeeze casting can be substantially used to improve the output of vital parts in the high-stress industries like car, airplane, and military. The possibility to cast more complex shapes with almost forged material strength creates new options of innovative materiality and lightweight design. Although technically modified due to the added cost of tooling and supporting equipment, in the long term lower machining costs, improved reliability and quality of parts produced all contribute to the economic advantage of long term use of squeeze castings as an economical alternative to High-performance applications. The following research directions are recommended to focus on optimization of process parameters, an extension to the use of the high-melting-point alloys, and the introduction of quality-monitoring conditions in the real-time.

6.1 Future Work

The prospective study in the sphere of squeeze casting should be aimed at elaboration of the series of high-tech materials processed with its help. Though most studies have been done on aluminum and magnesium alloys there is great promise in the potential application of squeeze casting to composite materials and other alloys with high performance like titanium and nickel-based superalloys. The study of the microstructural behavior and phase transformation of these material in different pressures and in

different years of solidification is able to open new doors in aerospace, biomedical and defense applications.

Process optimization and the production of process control systems in real-time is another major area of future work. Advancement of simulation models and their adoption in AI-based monitoring may help to improve the predictability of a process, minimize defects, and guarantee closer dimensional tolerances. The research must focus on the precondition of improvement of die design, cooling rates, and pressure regulation in order to ensure high mechanical properties and quality control. Also, automation and Industry 4.0 solutions can be adopted to turn the squeeze casting method into a cost-effective process of producing castings on large scale.

The sustainability and the life-cycle of squeeze casting should be highlighted. Investigations ought to conduct an evaluation of the consumption of energy, material utilization, and recyclability of cast components in relation to the traditional die casting processes. The use of environmental friendly lubricants and die materials to minimise environmental effects can also be studied by researchers. By these developments, squeeze casting has the potential to become more sustainable and flexible manufacturing process, presenting a perfect solution to create lightweight, high strength and geometrically complex parts.

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