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Systematic Review on Investment Casting

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Abstract: ***The Investment casting (IC) method is now used to make all precision components in the medical, hydropower, defence, car, and other sectors. IC has a wide range of applications and is well-known for its ability to make complex near-net form items with great dimensional precision and surface polish. Various scholars are making ongoing efforts to investigate the topic of investment casting. This publication offers a comprehensive survey of the studies in this vast topic. It emphasises improvements in the earliest stages of the investment casting process. It focuses on pattern creation improvements, mould composition, casting materials, and typical flaws, as well as preventative actions.***
Keywords: Investment casting, Pattern modelling, Mould, TiAl alloys, defects

I. INTRODUCTION

Investment casting is such a broad subject, it has seen several developments. According to our findings, the works published mostly focused on modifications to the developing pattern, cast metal, and the appropriate materials used in mould production, as well as the analysis of flaws and remedies without changing the fundamental framework of conventional IC. Because the shape of our cast is mostly determined by the pattern used in the process, it is vital for us to research and improve the sort of pattern we employ in order to obtain a high-quality cast. We do this through researching pattern-making processes, wear analysis, and the optimal material for pattern-making. 3-D printing is the technique of choice for creating complicated and detailed designs. Its merits include dimensional precision and near-net form cast, but the method is time - consuming.

We use laser sintering for wear analysis in order to have a cheap and efficient technique of analysing the pattern. Selective laser sintering also improves the pattern's tensile strength. The accuracy of designs is always affected by the varied materials employed to create them. For economic efficiency, Portland cement and silicone rubber are utilised in investment casting to achieve the most exact designs. In the instance of TiAl alloys, this research emphasises the relevance of investment casting. Because of their poor flowability, reactivity at high temperatures, and high melting point, these alloys are unsuitable for traditional casting procedures such as sand casting and die casting.

This article discusses four distinct types of refractory materials and binders. The viscosity of the zirconium-based slurries was compared, as well as the influence of powder to binder ratios on the mould strength. Mould reactivity and hardness were tested between alumina and zirconia-based slurries. Investment casting isn't perfect, and defects such as misruns, gas holes, and shrinkage porosity can occur. However, these defects can be significantly reduced by optimising casting parameters such as casting temperatures, shell thickness, and insulation to produce the desired output, which increases the process' efficiency. The difficulty in delivering liquid flow necessary during final solidification of the solid phase, which is denser than the inter-dendritic liquid, causes porosity owing to isolated pockets.

The mushy zone must be kept to a minimum to avoid inter-dendritic shrinking. The breadth of the mushy zone is determined by the temperature gradient and the Alloy's non-equilibrium freezing range. The paper illustrates how shell thickness and well-designed insulation may assist generate a steeper temperature gradient at the metal/mould interface and a slower cooling rate, both of which are necessary to keep the mushy zone limited and ease feeding through it. The study also shows how increased shell thickness affects fill-ability and grain structure. The water saturation method is used to determine the porosity of the shell. X-ray flaw detection and fluorescence detection are used to evaluate casting quality.

II. RESEARCH METHODOLOGY

The goal of a systematic review study is to locate, classify, and present data from chosen research publications in a logical and systematic manner. The first stage was to gain a thorough grasp of the investment casting process, which was followed by the division of subtopics, such as the materials used, the matching design and mould creation, and the examination of any faults. The goal of this evaluation is to emphasise progress in each of the aforementioned categories.

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Pattern		Mold making		Alloys used for casting		Defects		Post processing	
Keyword	No. of documents	keywords	No. of docs	Keywords	No. of docs	Keywords	No. of docs	Keywords	No. of docs
Casting	169,320	Casting	169,320	Casting	169,320	Casting	169,320	Casting	169,320
Investment casting	8072	Investment casting	8072	Investment casting	8072	Investment casting	8072	Investment casting	8072
Mold	3088	Mold	3088	Mold	3091	Mold	3088	Mold	3088
Pattern	868	Refractory Material	429	Metals	2117	Defects	706	Post Processing	88
				Alloys	1684				
Total number of docs taken	9	Total number of docs taken	11	Total number of docs taken	3	Total number of docs taken	11	Total number of docs taken	5

Fig 1: Table representing data extraction

The following is the procedure:

1) Gaining a comprehensive grasp of the investment casting process in its entirety.
2) Define the domains that will be addressed
3) Task distribution and assignment to each team member
4) In-depth study into certain subjects
5) Refining the information gleaned from multiple research articles, then drafting a preliminary copy for each domain.

III. RESEARCH OBJECTIVES AND QUESTIONS

The investment casting method as a whole has stayed unaltered, according to the initial research; what attracted the researchers was the variance in pattern design and mould elements with different materials, as well as related flaws. The following are the questions that we will address throughout this paper:

The following are the questions that we will address throughout this paper:

1) What are the latest breakthroughs in pattern making?
2) Why are some materials (TiAl alloys in this example) unsuitable for traditional moulds, and what changes are required to the mould ingredients as a result?
3) What are the most common flaws, and how may they be avoided?

IV. SEARCH STRATERGY

Collecting and summarising data on each topic are the processes involved. Scopus and Google scholar were used extensively in the research, with Scopus being a key contributor to the data obtained. Papers from a variety of sources were included in these EDS (conference proceedings, research publications, and journals). Up any domain, Google Scholar was utilised to fill in any gaps in knowledge. The automated string search was created using a mix of key phrases taken from the stated research questions, keywords from the many research articles found through the search, and a synonyms list.

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V. EXCLUSION AND INCLUSION CRITERIA

The relevancy of the material and if the research questions were answered were used as inclusion criteria. Although several research publications were not open to the public, their abstracts provided us with a basic overview of the issue as well as technical data that would be extremely useful for this systematic review.

1) *Exclusion Criteria 1:* Non-English research articles
2) *Exclusion Criteria 2:* Short papers (less than 3 pages)
3) *Exclusion Criteria 3:* Unrelated to the issue and incapacity to respond to the above-mentioned research questions.
4) *Exclusion Criterion 4:* Data from books, posters, forums, presentations, and other sources.

The data collecting procedure is challenging to convey in four easy stages. In order to gain a thorough knowledge of the data inclusion and exclusion procedure, a final collection of 29 research papers was chosen for this systematic review (fig. 2).

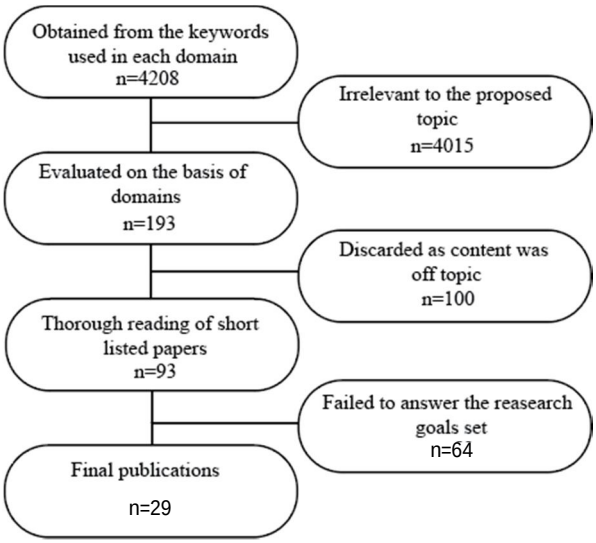

Fig 2: Data extraction methodology

VI. PATTERN MODELLING

Investment casting relies heavily on patterns. It will determine the form of your final casting, therefore we must create a pattern that will result in a casting that is close to net shape with the fewest faults. Pattern material, wear analysis, design testing, and the methods by which the pattern is produced or pattern modelling are all examples of innovations in patterns.

3-D printing is one of the technologies for creating patterns. Three-dimensional printing (3DP) is described as the layer-by-layer technique of combining materials to create things using 3D model data. 3-D printing can create any design based on intricacy, but the main problem is that it takes several days to create the pattern, sometimes many days, because 3-D printing is a very slow process.

To improve the pattern quality, attempts are being made to use the laser sintering technology for wear analysis. Wax injectors are primarily used to create the wax pattern of single crystal superalloy turbine blades, which must have complicated forms and great dimensional precision. The initial stage in the investment casting process is to create the wax pattern, which is subsequently transferred to the ceramic shell and finally to the final casting. As a result, the wax pattern's quality plays an important part in the entire casting process, which is a time-consuming and tedious operation. Furthermore, the wax injector machine has a considerable impact on the wax pattern quality. Currently, dimensional instability, misrun, bubbles, surface roughness, deformation, and adhesion are common difficulties with wax patterns created by household wax injectors, severely limiting the formability of the castings.

As a result, a new method for controlling wax flaws must be developed. SLS (selective laser sintering) is a novel approach for generating a wax pattern for a casting that is equivalent to traditional production processes. SLS is better to traditional technologies in the fabrication of wax patterns with complicated geometries because it is not limited by moulds. The energy source for SLS is a laser beam. When the laser beam hits the manufacturing platform, it creates a temperature field surrounding it. A Gaussian distribution may be seen in the temperature field.

Individual and irregular polystyrene (PS) granules are melted and sintered necks are formed using laser energy. The capacity to mould complicated things, make goods with a smooth surface, and great precision are all advantages of the investment casting technology. This is directly tied to the wax pattern employed; if the wax has a precision geometry with an exact shrinkage estimation throughout the casting process, the result will follow the plan, and vice versa. The level of roughness and accuracy of wax moulds constructed of Portland cement and Silicone Rubber are compared in this study.

VII. MATERIALS AND CORRESPONDING MOULD MATERIAL

Due to its low density, burn resistance, and good mechanical capabilities up to 800oC, TiAl alloys are developing as a viable high temperature structural material in the aviation and automotive industries. TiAl alloys are not suitable for other casting methods due to their low ductility, high melting temperature, reactivity, and poor workability. Investment casting is ideal for casting TiAl alloys because of its excellent surface smoothness and dimensional precision. The traditional investment casting mould ingredients (refractory material consisting of Al2O3- SiO2 and siliceous binders) have a strong reactivity towards TiAl alloy melt (alloy-refractory interaction effect). When solidification begins, diffusion processes become extremely sluggish, and if the metal–mould contact continues, a composition gradient from the surface to the inside of the casting may form.

When a reaction takes place, the reaction products may emerge on the casting surface (if they are not soluble in the liquid metal or have a slow dissolution rate), or they may dissolve quickly and go undetected (as it happens with TiO and TiO2, that dissolve very fast in liquid titanium, increasing its overall oxygen content). The -phase is formed as a result of this reaction, which degrades the surface quality and changes the mechanical characteristics of the titanium casting. This section discusses the different changes made to mould ingredients to achieve high-quality casting. Primary coating materials include ZrO2, Y2O3, Al2O3, MgO, and CaO, which are thermodynamically stable at high temperatures. The major coating binder zirconia sol is commonly utilised.

Binder	ZrO2 (SiO2) (%)	pH	Density (g/cm^3)	Viscosity (mPa-s)
Zirconium acetate (ZA)	22.0-24.0	4.0	1.34	8.4
Ammonium zirconium carbonate (AZC)	18.0	9.8	1.38	4.3
Silica sol(S)	29.0-31.0	9.5	1.20	4.3

Fig 3: Composition of primary slurries

The main slurry was made with CaO-stabilized ZrO2 powders (325 mesh) and binders such as zirconium acetate (ZA) and ammonium zirconium carbonate (AZC). Each of the three binders was completely mixed with the ZrO2 powders. To reduce surface tension, Victawet 12 (conc. 0.5 wt.%) was utilised as a surfactant in the slurries. As a defoaming agent, octanol (0.3 wt%) was utilised.

Surface finish is influenced by the viscosity of primary and subsequent coatings, which is dictated by the powder to binder ratio as well as the characteristics of refractory and binder materials. For all three slurries, viscosity rises as the ratio of powder to binder rises. The viscosity of the ZA slurry is higher.

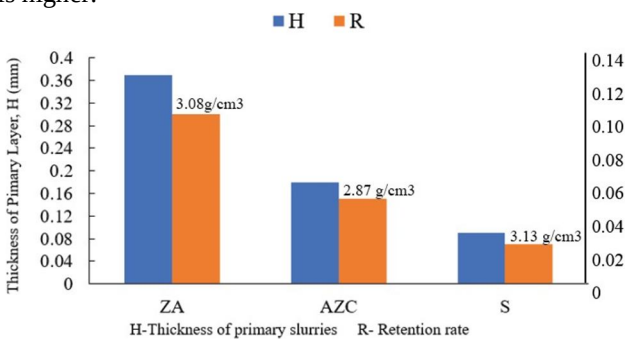

Fig 4: Thickness of primary layer and retention rate for three different slurries. It implies that density and viscosity are not interdependent

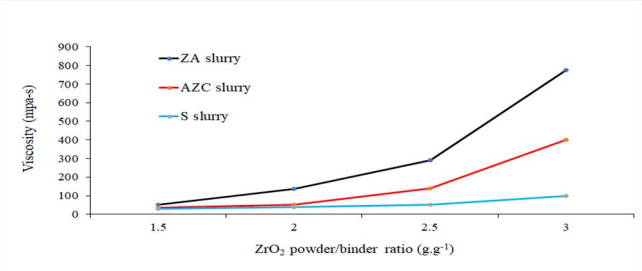

Fig 5: Viscosity increases with increase in powder/binder ratio

The ZA slurry has the highest retention rate (0.11 g/cm3) and main layer thickness (0.37mm). The effect of changing the powder to binder ratio on the retention rate and thickness of the main layer was investigated using ZA slurries. Peeling faults were seen at lower power to binder ratios, whereas cracking was seen at higher levels. For ZrO2 powder and ZA binder, the optimal powder to binder ratio is around 2.5:1.

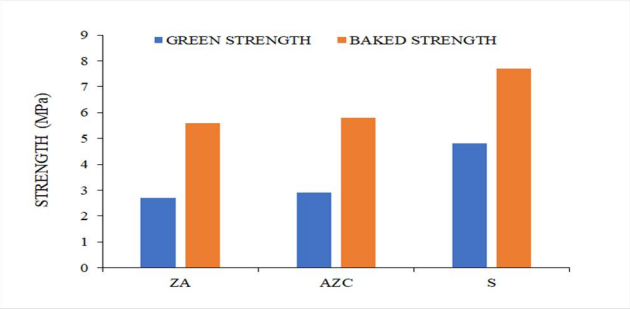

Fig 6: Green strength and baked strength of the three primary slurries

Jia et al investigated the interfacial response of Ti-46Al and ZrO2 and Al2O3 ceramic shell moulds. The metallographic analysis revealed that there was a distinct interaction between the ZrO2 mould and the alloy melt, but the Al2O3 mould produced no obvious reaction products. It was discovered that Zr spread into TiAl from both the binder and the refractory, but not from the alumina mould. In terms of microhardness, the zirconia mould had a 325m thick surface hardened layer, but the alumina shell mould only induced a hardness increase of less than 20% of the zirconia mould in a thin surface layer less than 80m thick. The TiAl alloy reacted violently with the ZrO2 shell mould, although the interaction with the Al2O3 shell mould was minor. For investment casting of TiAl-based alloys, an Al2O3 mould is a viable choice. The Zr sol binder, on the other hand, has to be enhanced.

VIII. DEFECTS AND CORRESPONDING SOLUTION

A. Misruns and gas holes (for TiAl alloy castings)

Misruns and gas holes were the major faults discovered in early work with thin-wall TiAl alloy turbochargers made by investment casting, due to the alloy's low fluidity and gas entrapment. To address these flaws, cast parameters such as centrifugal rotation rate and mould preheating temperature were improved, while the shell mould structure was modified to increase TiAl alloy filling capacity. Based on the foregoing optimization, pouring tests were carried out using a vacuum induction melting furnace with a water-cooled copper crucible. They can significantly increase mould filling capacity while lowering failure rates.

B. Shell moulds' deformability (for TiAl alloy casting)

The majority of TiAl components are now made using an investment casting technique. Cracks, porosities, and surface flaws are now the most common difficulties in investment casting of TiAl alloys. It has been discovered that by optimising the composition and qualities of the shell moulds, casting flaws may be decreased. As a result, improving the refractory nature of shell moulds for TiAl alloy investment castings is critical to eliminating flaws. Because of the advantages of the investment casting process over other casting processes and forming technologies, most TiAl parts, especially complex components, are produced by it. This is due to the high brittle ductile transition temperature, narrow solidification range, and reactivity of the melt with mould materials. Because TiAl alloy melt has a high chemical reactivity and can react with almost all refractory materials, resulting in deteriorated inner and surface quality of investment castings, the choice of refractory materials for the shell mould surface becomes a critical issue in the development of ceramic shell moulds.

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IX. DEFORMABILITY

Chen et al. investigated how to increase the deformability of a ZrO2 ceramic shell mould for TiAl investment casting. In the ceramic shell mould, high polymers were also applied, and the impact was evaluated systematically. The stress-strain curves of the shell moulds with varying amounts of high polymers were compared before and after baking, as illustrated in Figs. 7 and 8. The strength of the shell moulds with high polymer addition rose before baking and reduced after baking, resulting in an improvement in shell deformability. Because of the decreased surface fissures in the shell mould, this strategy of introducing high polymers to promote deformability can also aid reduce sand cleaning effort on TiAl castings.

The following findings were made after reviewing the research developments on the deformability of shell moulds for TiAl alloy castings:

1) There is presently no standard method for measuring the deformability of shell moulds. Bending strength, both at room temperature and at high temperatures, is now commonly utilised to characterise deformability. Recently, the wedge test and I-shaped specimen procedures have been suggested and used.

2) Changing the composition of the shell mould is the most common technique to increase deformability, and two methods have been reported: adding dextrins, fibres, polymers, or natural based materials to the back layers of the shell mould, and utilising alternative back layer binders. In the first case, the leftover porosities caused by additives after baking result in a loss in shell mould strength; in the second case, lowering the viscosity of the slurry reduces the binding strength between slurry and sands. The enhanced strength before baking, as well as the lowered strength after baking, are both beneficial for shell mould preparation and improved shell mould deformability. However, the current strategies for improving deformability were only relevant to a few basic castings.

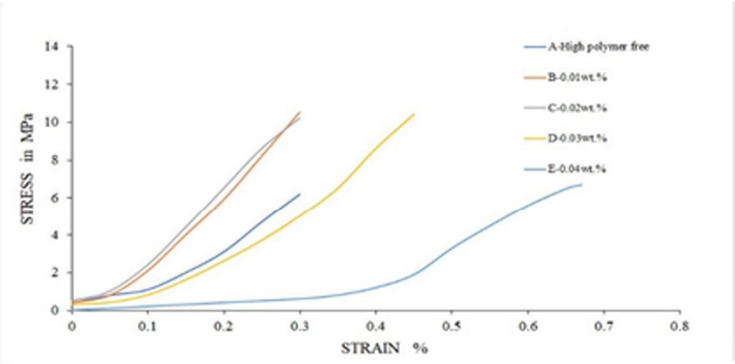

Fig 7: Stress vs strain curve of moulds after

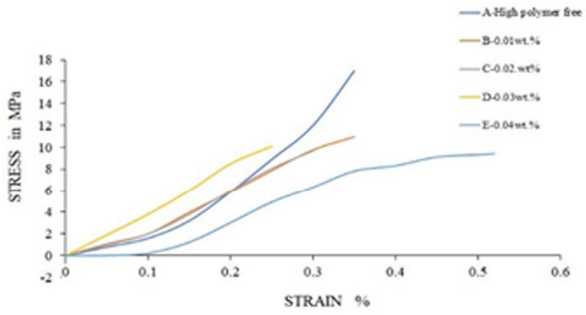

Fig 8: Stress vs strain curve of moulds before

X. POROSITY SHRINKAGE

1) Internal shrinkage during the solidification process in the gating systems causes porosity, which is one of the casting flaws. Based on the gating system design, the internal shrinkage porosity of an item produced of commercially pure titanium (CP-Ti) is predicted. Internal shrinkage porosity occurs on the greatest section of three gating system configurations. Internal shrinkage porosity is lowest in the gating system design with ingates cross section area: 78.5; 157; and 128.5 mm2.

2) To eliminate shrinkage porosity defects in jewellery castings, alloy materials with a sufficient melting temperature and small solidification range should be preferred, as should the jewellery structure and pouring method, and castings with dramatically different structures should not be poured at the same time.

3) In another investigation, the bottom of the casting system was saturated in cold water to drive solidification upward from the bottom. According to simulation data, this procedure considerably minimises the likelihood of shrinkage faults in castings.

4) X-ray computed tomography was used to examine the shrinkage hole, shrinkage porosity, and shrinkage distribution of casted TNT and RHT explosive charges. Crystal phase shift, solid shrinkage, and gas escape during solidification are the major causes of shrinkage holes and shrinkage porosity. The critical solid phase approach may be used to forecast the shrinkage hole and shrinkage porosity distribution in a casted explosive charge when feeding length is taken into account. Heat insulation between the riser and the mould, as well as heat preservation on the riser and riser dimension growth, can all help to reduce shrinkage holes and shrinkage porosity during the casting process.

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The Effect of Shell Thickness, Insulation and Casting Temperature on Defects Formation During Investment Casting of Ni-base Turbine Blades

Shrinkage at the tip-shroud and cord junction is a typical casting issue in blade investment casting. Because of the high temperatures involved, grain structure is extremely important in these castings to prevent creep. Increased shell thickness was shown to assist extend the feeding distance in thin sections, preventing inter-dendritic shrinking. In thin sections, it was also discovered that grain size is unaffected by shell thickness. Slower cooling due to additional insulation and a steeper temperature gradient at the metal mould interface generated by the larger shell not only helps to reduce shrinkage porosity, but also improves fill-ability in thinner portions.

Shrinkage is heavily influenced by the thickness of the ceramic shell. Shell thickness, which is crucial for casting thin, complicated forms, determines the heat absorption capability of ceramic. The heat absorption capacity is essential in thinner sections and at abrupt junctions because it affects the heat transfer coefficient and the temperature gradient in the metal next to the mould wall. With rising heat gradient, the breadth of the mushy zone shrinks, allowing metal to flow into shrinkage pores. Insulating smaller parts reduces the cooling rate, reducing the length of the dendrites and resulting in a more flat solidification front. The larger temperature gradient and slower cooling rate maintain the breadth of mush narrower, allowing metal to feed via developing dendritic arms for a longer distance and therefore reducing shrinkage not just where the solidification front meets but also throughout the solidification process.

The influence of metal pouring circumstances on defect formation:

The influence of the metal's pouring temperature and velocity on the casting's solidification kinetics was investigated. An suitable selection of these parameters was tested in order to get the casting without shrinkage faults, which is vital for foundry practise. The velocity fields were calculated using the Navier-Stokes equations and the continuity equation, while the temperature fields were calculated using the heat conductivity equation with the convection term.

Three different metal pouring parameters were used in the numerical simulations. When the mould cavity is entirely filled with liquid metal, the solidification process begins efficiently for a certain form of the casting. The solidus line closed at the upper section of the casting is evident at the ultimate solidification time of the casting-riser system. If the casting process was carried out at a lower pouring temperature or with a higher molten metal pouring velocity, this predicts the production of shrinkage flaws at this location. If the casting process was carried out using conventional pouring conditions for the mould cavity, this circumstance was not seen. Because the riser is cut off and re-processed, the solidification end took place in the riser in this case, which is desirable. It also shows that the conical-shaped riser did its job and that the casting was free of flaws.

XI. CONCLUSION

Three primary approaches for pattern research and development in construction and wear analysis include 3-D printing, laser sintering, and the usage of portland cement and silicone rubber. The sole disadvantage of creating or manufacturing patterns is the time limitation imposed by the sluggish 3-D printing process. The use of laser sintering with silicone rubber makes the pattern stronger, stiffer, and more robust, resulting in better investment casting yield.

Titanium alloys have been a godsend to the aviation and automotive sectors due to their extraordinary qualities. This article explains a few of the numerous methods in which these alloys may be casted utilising investment casting. The slurry with zirconium acetate binder had the maximum viscosity, susceptibility, and plate weight, which can be attributed to the binder's high viscosity. The surface quality of completed castings is determined by the correct powder/binder ratio. For practical manufacturing, a 2.5:1 powder/binder ratio for ZrO2 powder and zirconium acetate binder is recommended.

When Al2O3 was used as a refractory material and Zr sol was used as a binder, the alumina had no reactivity with the TiAl melt, but the Zr binder did. To get a high-quality product in this scenario, the Zr sol binder must be modified.

In investment casting, flaws such as misruns, gas holes, and shrinkage porosity are common. Shrinkage is greatly influenced by the thickness of the ceramic shell. Shell thickness, which is crucial for casting thin, complicated forms, determines ceramic's heat absorption ability. Insulation reduces the cooling rate, resulting in a flatter solidification front by reducing dendritic length. Reduced shrinking is aided by the circumstances created by a larger thermal gradient and a slower cooling rate. Organic fibres are introduced to the rear layers of the shell mould to improve gas permeability. The porosity of the shells rises as the percentage of organic fibres increases from 0 to 1.5, but the strength of the shells diminishes.

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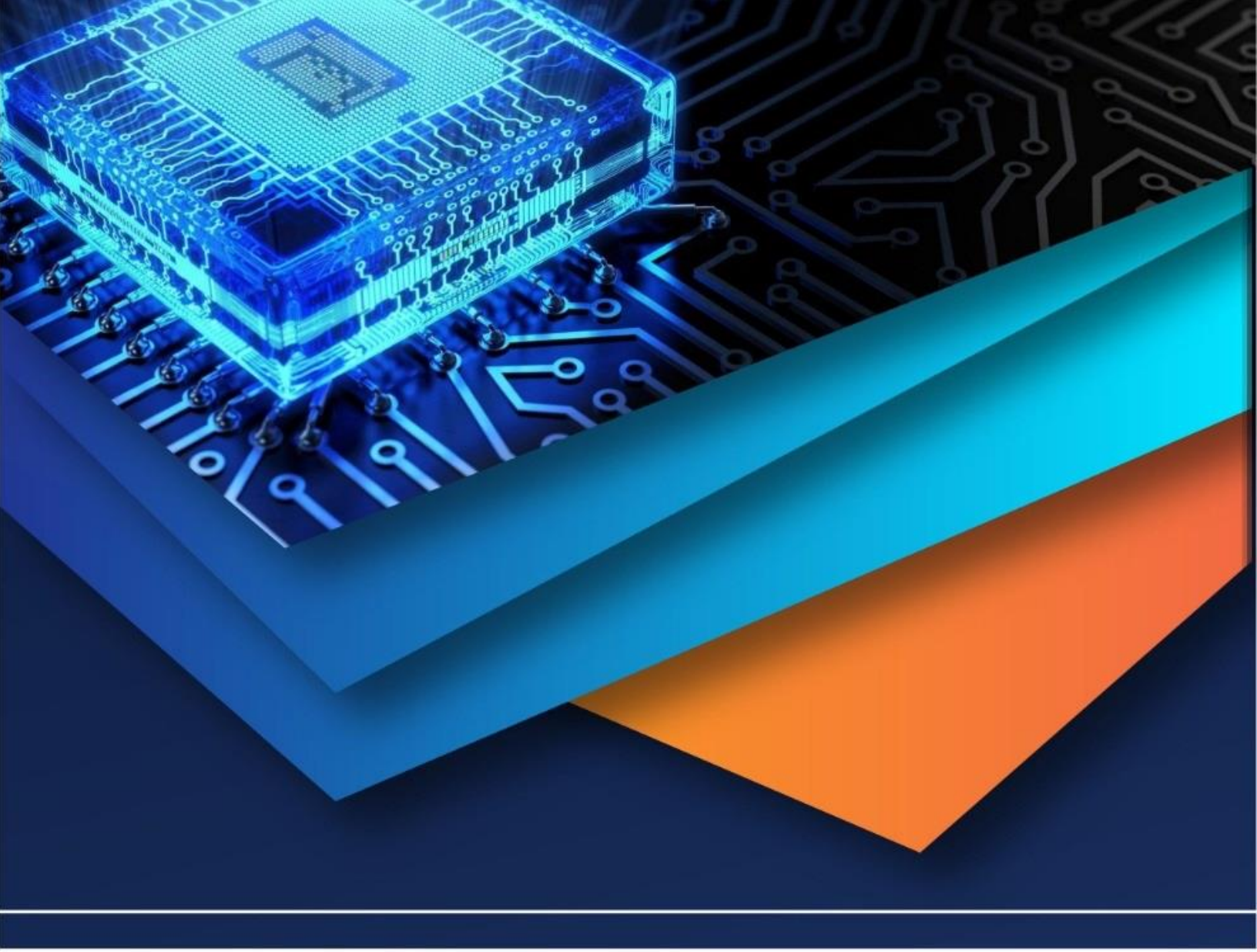

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