International Journal of Applied Engineering Research ISSN 0973-4562 Volume 18, Number 4 (2023) pp. 278-291
© Research India Publications. https://dx.doi.org/10.37622/IJAER/18.4.2023.278-291

# A Review on Casting and Testing of Bimetals

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**Abstract**

Metals have been existing for ages and the production methods to shape, form the metals as per the requirement for various applications in engineering are so many. The more sophisticated applications in today's advanced technological world calls for better materials to be sustainable for efficient functioning of the system and its longevity. Bimetal cylinders is one such advancement which has taken its own importance for industrial applications and one of the efficient manufacturing practices for producing bimetal cylinders in centrifugal casting. Understanding how molten metals behave during centrifugal casting, and how their properties change due to different process parameters has been a crucial field of study for a sound centrifugal cast. This paper deals with presenting the various combinations of metals used by researchers to develop, analyze and study the bimetal cylinders, its interface, the process parameters, methods etc to improve the quality of casts produced for various applications with less defects.

**Keywords**: Bimetals, Casting methods, Process Parameters, Testing methods.

## 1. Introduction

For the materials to be processed and used for the purpose of mankind, it is important to understand the behavior of materials during a variety of scenarios, applications and practice. Because the materials irrespective of their nature behave differently in different environments. This was possible to be understood only with atomistic levels allowed by quantum mechanics, which explains atoms and solids started in the 1930's. While the focus of properties of a material and its microstructure is the domain called material science.

There are different types of manufacturing processes to form the parts by converting the raw material into a finished product. Out of so many manufacturing practices in today's technological world, Casting is one of the old manufacturing practices which holds its importance and uniqueness where the liquid material is poured into a solid mold, which contains the required shape in the form of a cavity. Once this molten metal is filled in the cavity, it solidifies and forms the required shape. The principle of centrifugal casting technique is that it applies forces generated from the centripetal acceleration of a rotating mold[1]. Centrifugal casting produces a product with accurate dimensions and limited gas porosity.

Though Casting is a one of the old manufacturing practices, still there are a lot of gray areas for its development in the casting technology when it's compared to other manufacturing methods. The advancement of computers over the years have made the researchers study the process of casting technology considering many variables and thus changing the foundry from an art to that of a science. An important and difficult to be assessed practice is casting, because of the working conditions of it. Like there are changes in its phase, huge temperature differences, dynamic conditions, high speed of solidification, impurities, formation of voids, irregularities, grain formations, microstructures, etc. The most required, and also most complex, is the formation of the grain structure during solidification. The crystallization includes the formation of grains and nuclei growth, but also the formation of structure defects, phase changes in solid metal etc. The simulation softwares which also makes it possible to follow this phenomena occurring during the casting process will certainly aid to improve the casting manufacturing practice.

While the sound casts can be produced by refining the manufacturing process with the advancements in simulation and modern equipment, There are various applications which require components that are a combination of different metals instead of pure metal. An advantage of combining materials for casting is to bring in and utilize the unique properties of both materials into one. One such combination of two materials (if metals) to form a casting is called Bimetal. Bimetals are one of the simplest forms of metal composites, which may or may not be with reinforcements. As the name says, it is a combination of two different metals in the form of layers rather than mixing them like in alloy, to form the product. The bimetal gets bonded as one because of the metallurgical bonding, which forms between the two metals when it is capable to approximate the existence of atoms near the interface of two metals that would create repulsive and attractive force between them [32]. Hence the main advantage of a single material can be realized by compounding two materials with different properties to produce a bimetallic component. When the performance of one of the materials is high, rare and precious can be replaced to some percentage by combining them with another metal forming the bimetallic components, Which are widely used in the fields of deep space exploration, wind power, petrochemicals and ocean going ships, etc. Due to the difference of structure and performance in the bimetallic materials, the key of the composite in bimetallic components is characterized by the interface morphology and bonding characteristics.

After decades of research and development, the centrifugal casting of bimetallic composited roller and pipes have been achieved. For the bimetallic composited roller, the outer layer and inner layer are produced by the horizontal centrifugal casting and gravity filling casting, respectively. And both the outer and inner layers in the bimetallic composited pipe are produced by the horizontal centrifugal casting. The morphology of the bimetallic bonding interface is affected by the pouring temperature of the outer layer, intervals between inner and outer layers and rotational speed of casting mold. The effect factors of the bonding thickness are mainly pouring temperature and solidification method. The mechanical properties of composited components heavily depends on the bonding interface. During the centrifugal casting of bimetallic composited roller and pipe, the electromagnetic control, multi alloy modification and step heat treatment after centrifugal casting can improve the morphology and the uniformity of composition distribution in bonding interface, which lead to the improvement in bonding properties. The composited mechanism of centrifugal casting is mainly characterized by metallurgical bonding. [2]

The two metals or metal alloys form a metallurgical bonding (metal bonding) at the interface to constitute a single piece composite[3]. Existence of Metallic bond at the interface of two metal pieces causes accretion of product. These two metals together will complement each other in terms of mechanical properties, chemical, physical or economic. In making metallurgical bimetals‹ the main thing is the creation of metal bonding between two metallic components. Metallic or metallurgical bonding forms between two metals when it is eligible to approximate the existence of atoms near the interface of two metals that would create repulsive and attractive force between them. There are only certain metals that can be combined to form bimetals because of its chemical, physical and metallurgical properties.

The applications of such bimetal products are in chemical industries, petrochemicals, power plants, nuclear power plants and metals mining industries (Copper, Iron, and Steel). It's also widely used in the fields of deep space exploration, wind power, petrochemicals and ocean going ships, etc.

Bimetal cylinders are the most common type of components used in industries for its usage as bimetal pipes which are produced with centrifugal casting. In these industries bimetal pipes are widely used for heat converters, reformers, heat exchangers, reactors, condensers, pumps, radiation tubes etc. In applications, multilayer metals may be divided into corrosion resistant, wear resistant, or tool materials, thermal bimetals, electrical engineering, wire, contact, or anti frictional materials, materials for deep extrusion, for heat exchangers, or for domestic appliances, and so on. Bimetals significantly improve the production efficiency of components in various branches of industry.[4]

## 2. Materials and Methods

With the vast availability of materials for various applications, for production of bimetals Ferrous and Non Ferrous metals can be opted. While we can find there are certain combinations of metals on which some of the work has been done by various researchers. There are also few of the restrictions not to combine some metals as they react with each other or they fail to form the metallic bond with each other resulting in separation of two metal pieces.

The following are some of the metal combinations on which research has been carried out;

**Table 2.1**

| **Sl no** | **Shape** | **Metal -1** | **Metal -2** | **Method of Manufacturing** | **Testing Methods** | **Observations** | **References** |
|---|---|---|---|---|---|---|---|
| 1 | Hollow Cylinders | Aluminum | Copper | Vertical Centrifugal Casting | 1. Optical microscopy (OM)<br>2. Energy Dispersive X-Ray Spectroscopy<br>3. Scanning Electron Microscope) | 1. EDS & SEM were done to study the elemental composition of the analyzed volume.<br>2. The bonding between Aluminum and Copper at the interface were found to be weak due to metal oxide formations. | [5] |
| 2 | Hollow Cylinders | Aluminum 6061 | SiC (Reinforcements) | Vertical Centrifugal Casting | 1. Optical photomicrographs<br>2. Wear Tests<br>3. Hardness Tests | 1. Microstructures from Optical photomicrographs clearly help to understand the segregation of Si particles in the cast.<br>2. The primary Si particles formed were segregated as a graded layer in the inner periphery of casting leading to better hardness and improved wear resistance. | [6] |
| 3 | Bimetal Cylinders | Aluminum Alloy UNS A92011 | Brass UNS C38500 | Assembly Fit | 1. Compression tests<br>2. Ductile damage predictions using FEM software<br>3. SEM Analysis | 1. After the compression, a few samples with clearance fit showed a permanent joint between the center and the ring.<br>2. SEM analysis observed voids, microcracks, and cracks in specific areas of the maximum predicted damage.<br>3. Numerical simulations show that the ductile damage is higher in bimetal than in single metal made from aluminum alloy. | [7] |
| 4 | Bimetallic casting blank | Aluminum Alloy 2024 | Aluminum Alloy 6061 | Gravity Casting | 1. Isothermal compression to clarify the interface bonding mechanism | 1. It was observed that the size of grains near to the Al 6061 side is larger | [8] |

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| | | | | | 2. Electron backscattering diffraction (EBSD) pattern analysis using SEM.<br>3. HKL Channel 5 software | than that near to the Al 2024 side.<br>2. Gradual increase in stress was observed following which stress began to decline and level off, no obvious changes. Which was due to the interaction of strain hardening and dynamic softening.<br>3. The width of the interface bonding layer increases with increasing compression temperature and decreasing strain rate. | |
| 5 | Bimetal Cylinders | Aluminum-silicon alloy (4032) | Bronze (20%Cu) | Centrifugal casting with a solid-liquid method | 1. Etching process to uncover the microstructure.<br>2. SEM-EDS (Quanta x50 SEM Series)<br>3. Metallurgical microscope (PME 3, Olympus, Japan). | 1. The Intermetallic compound thickness increases in line with the increase in temperature of the first frozen layer.<br>2. It is observed there are three layers formed, named as interface bronze (layer B), interface & interface aluminum-silicon alloy (layer A).<br>3. The width of the interface gets longer as the temperature of the first frozen layer increases<br>4. The hardness of the bond interface is increased compared to the hardness of the base metal.<br>5. The wear of the interface layer shows the lowest among all of the layers.. | [9] |
| 6 | Bimetal Cylinders | Aluminum | Magnesium | Centrifugal Casting | 1. SEM equipped with energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD)<br>2. Atomic force microscopy (AFM) | 1. Results showed that increasing the melt to solid volume ratio from 1.5 to 3 resulted in diminishing metallurgical bonding | [10] |

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| | | | | | | at the interface.<br>2. The image of Al surface showed that the surface was rough in atomic dimensions, which can result in the formation of gas pores in the interface. | |
| 7 | Bimetal Cylinders | Aluminum | Copper | Centrifugal Casting | 1. Metallurgical microscope (PME3, Olympus, Japan)<br>2. SEM-EDS (Quantax50 SEM Series).<br>3. Etching process to uncover the microstructure. | 1. It is observed from the results that the width of the interface increases as the mold rotation increases.<br>2. The Interface hardness and wear are increased compared to the base metal.<br>3. Centrifugal casting with mold rotations speed of 350rpm was recommended for aluminum-copper bimetal bushing applications | [11] |
| 8 | Bimetal Plates | High chromium cast iron | Low Carbon Steel | Surface liquid-phase sintering | 1. Quenching<br>2. Tempering<br>3. Heat Treatment | 1. A diffusion zone with a width of approximately 37 lm and a troostite structure formed on the HCCI side by the interface | [12] |
| 9 | Ring blank | 40Cr Steel | Q345B Steel | Vertical Centrifugal Casting | 1. OpticalMicroscopy (OM)<br>2. SEM - EDS<br>3. Tensile tests<br>4. Shear tests | 1. Increase in rotating speed resulted in increase of convective heat transfer leading to poor bonding interface.<br>2. Centrifugal force ensures sufficient contact between the metals promoting mutual diffusion in the transition layer, resulting in a strong metallurgical bond.<br>3. Solidification is characterized by a gradual cooling process, progressing from the outer to inner | [13] |

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| | | | | | | layers and from the surface toward the center layer. | |
| 10 | Strips | Aluminum AlSn6Cu | Aluminum Al99.5 | Horizontal continuous composite casting | 1. 2D Finite Element simulations<br>2. Metallurgical Study | 1. The thickness ratio of the layers and the initial temperature of the first layer were found to be the most important parameters.<br>2. 3D finite element model was developed to gain a more realistic description of the temperature and fluid flow conditions in the composite casting | [3] |
| 11 | Bimetallics tubes | T-11 steel | SS310 | Centrifugal casting | 1. Micrometer microscope.<br>2. SEM<br>3. Hardness tests<br>4. Twist test | 1. The shear strength at the bond line was improved due to metallurgical bond between SS310 & T-11 during the extrusion process.<br>2. Transverse rings from annealed tubes withstand severe deformation without separation of the layers during a twist test developed in this study.<br>3. Tubes produced of SS310 on a T-11 steel base, are uniform in cladding and wall thickness, and possess uniform microstructures from end to end of tubes and from tube to tube. | [14] |
| 12 | Bimetallic Pipe | Aluminum | Copper | Vertical Centrifugal Casting | 1. EDS.<br>2. SEM | 1. The bimetal casted at 1320 rpm better than the other ones.<br>2. Factors such as mold preheating, rotational speed, controlled pouring of metals, and solidification time of metals are influential in final bimetal cast.<br>3. To produce better casts it is | [15] |

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| | | | | | | important that layers are clean without oxides or the process must be done in an oxygen free environment. | |
| 13 | Bimetal Composite | Stainless steel (2205) | Low carbon steel (AH36) | Hot rolling process | 1. Annealing.<br>2. Optical microscopy (OM)<br>3. Electron backscattered diffraction (EBSD)<br>4. Tensile tests<br>5. Tribological tests | 1. The width of the bonding interface was significantly affected due to its annealing temperature.<br>2. The mechanical wear in the chloride solution dominated the total wear volume loss of duplex stainless steel of composite. | [16] |
| 14 | Strips | Steel | Babbitt alloy | Liquid–solid compound casting method | 1. Etching<br>2. Optical microscope<br>3. SEM (FEG)<br>4. Energy-Dispersive X-ray Spectroscopy<br>5. Microhardness tests | 1. When Bi was added, the interfacial microstructure and Babbitt–steel wettability of the Sn interlayer were found to improve.<br>2. It was concluded that the Sn–Bi interlayer alloy's shear strength and ductility can both be enhanced by maintaining a low Bi addition percentage (≤1 wt%). | [17] |
| 15 | Bimetal Cylinders | Aluminum | Brass (CuZn35) | Vertical Centrifugal Casting | 1. X-Ray diffraction<br>2. Optical microscope<br>3. EDS | 1. Results show the composition of elements of Al, Cu and Zn precipitates in the matrix and finally Al/Al2Cu anomalous eutectic structure neat to Al base metal.<br>2. Increased rotational speed results in reduction of thickness of interface layer.<br>3. Interface layer reduction may be due to higher conduction rate at higher rotational speeds.<br>4. Entrapped | [18] |

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| | | | | | | gas pores found at aluminum melt due to use of solid brass rings. | |
| 16 | Bimetal Cylinders | Aluminum | Copper | Vertical Centrifugal Casting | 1. SEM<br>2. Optical microscope<br>3. Microhardness test | 1. Due to increase in rotational speed, cooling rate also increases resulting in thinning of interface and increasing the nucleation sites.<br>2. EDS results show there are 4 discrete layers of Cu side.<br>3. Microhardness values decrease at the interface, while it increases near the Cu side due to intermetallic compound formation. | [30] |
| 17 | Bimetal Cylinders | Aluminum | Brass | Vertical Centrifugal Casting | 1. X-Ray diffraction<br>2. Optical microscope<br>3. EDS<br>4. Image J Software | 1. The metallurgical joint in this work is due to conditions provided by multiple mechanical forces involved and also due to solid diffusion at the end of the solidification process.<br>2. EDS results show 4 discrete layers and finally Alpha-Al/$Al_3Cu$ anomalous eutectic structure near the aluminum side. | [31] |
| 18 | Bimetal Cylinders | Aluminum | Magnesium | Vertical Centrifugal Casting | 1. SEM<br>2. X-ray Diffraction<br>3. Energy-Dispersive X-ray Spectroscopy | 1. Increasing volume ratio from 1.5 to 3 results in diminishing metallurgical bonding in Al/Mg interface, since the force of contraction overcomes the resultant force acted on the interface.<br>2. The images of the Aluminum surface showed that the surface was rough in atomic dimensions, which results in the | [10] |

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| | | | | | | formation of gas pores in the interface. | |
| 19 | Bimetal Cylinders | High carbon steel | Low carbon steel | Centrifugal composite casting | 1. Thermo mechanical treatment<br>2. SEM<br>3. Optical Microscope<br>4. Hardness tests | 1. In Liquid-liquid composite casting technology, the high-carbon steel and the low-carbon steel were bonded together by micro mass transfer.<br>2. The novel bimetal has a unique microstructure, in which four different regions including low-carbon steel region, interface region, fresh fully pearlitic region and conventional pro-eutectoid ferritic/pearlitic region were found.<br>3. The fully pearlitic microstructure was a new finding. | [19] |
| 20 | Bimetal Cylinder | Aluminum | Copper | Horizontal Centrifugal Casting | 1. SEM<br>2. Optical Microscope<br>3. Hardness tests | 1. A specified temperature for the first metal and then pouring second metal creates a metallurgical bond with proper quality.<br>2. If the temperature is too high the intermetallic compounds create an interface between two metals.<br>3. if the temperature is too low metal oxides glues and cool the second melt if the temperature is too low and sometimes no bond is formed.<br>4. For a better metallurgical bond at the interface, the surface of Copper should be clean, oxide free, and an oxygen free environment. | [20] |
| 21 | Bimetal | High | Ductile cast | Vertical Axis | 1. MAGMA Soft | 1. With the | [41] |

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| | Mill Roller | Chromium | iron | Centrifugal Casting | software<br>2. Metallographic analysis | mathematical model thus presented in this paper, at, different geometries of the mold, filled by the fluid and at different angular velocities solutions can be obtained for the free surface of a fluid under conditions of rotation at a constant angular velocity ω and under the action of the earth's gravitational field. | |
| 22 | Bimetal Milling Roller | Synthetic low-alloy Cast iron | Gray iron | Centrifugal casting | 1. Optical microscope<br>2. Microhardness tests | 1. As the distance from the outer surface of the billet increases due to the decrease in the rate of solidification, the microstructure becomes slightly coarser.<br>2. It was found that there was uniformity of hardness over the cross section of the layer.<br>3. The bimetallic rollers produced by the analyzed technological process showed a good wear resistance. | [42] |
| 23 | Bimetal Cylinders | Titanium | Copper | Extrusion & Deposition | 1. Tensile tests<br>2. Compression test | 1. There is a decisive influence on the obtained values of mechanical properties determined from the compression test with respect to the ratio of the sample height to the diameter.<br>2. The hardening curve according to Swift's Eq correctly describes the hardening process of the Ti/Cu bimetal in the direction of the compressive force. | [21] |
| 24 | Bimetal | Aluminu | Copper | Staggered | 1. Optical | 1. The increase | [40] |

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| | laminated tubes | m | | spinning Process | Microscope<br>2. SEM<br>3. Transmission electron microscopy (TEM, JEOL-F200)<br>4. Tensile tests | of the thinning rate is conducive to the interface bonding as per the fracture morphology.<br>2. The microstructure on both sides of the interface becomes finer and more uniform when the spinning reduction is increased.<br>3. The yield strength (YS) and ultimate tensile strength (UTS) of laminated tube increase first and then decrease with increase of thinning rate. | |
| 25 | Pipe | Aluminum Alloy A5086 | Copper C12200 | Friction stir additive manufacturing | 1. ABAQUS software<br>2. SEM<br>3. Microhardness test<br>4. Tensile test | 1. Due to the severe plastic deformation in the stir zone, the aluminum−copper intermetallic compounds (CuAl and Cu Al ) are formed in the stir zone.<br>2. The contribution of heat due to plastic deformation is 8% to 13% of the total heat generated during the process as per the simulation results.<br>3. The hardness of the stir zone on the aluminum alloy side increases compared to the aluminum base metal. | [23] |
| 26 | Cylinders | Copper–tin alloy (CuSn6) | Pure copper | Static Compound casting | 1. Mechanical Testing<br>2. Structural analysis | 1. A cohesion with a sharp transition zone between the metal layers can be achieved under favorable thermal conditions by forming a solid solution at the interface.<br>2. The base temperature is an | [24] |

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| | | | | | | important parameter for large scale metallurgical bonds.<br>3. A multi-step casting setup with a stationary mold system yielded a high bonding quality. | |

## 3. Conclusion

The manufacturing methods for production of Bimetals in the form of cylinders[6] [9] [10] [20] [21], blanks [8] [13], tubes/pipes/rods[15], [22]–[24], or strips [3], [25], etc with different combinations and shapes are listed in the above Table 2.1.

Irrespective of the combinations of different metals and shapes, or the method of manufacturing to produce bimetals, the need for the particular combinations depends on its various applications. The bimetal gets bonded as one because of the metallurgical bonding, which forms between the two metals when it is capable to approximate the existence of atoms near the interface of two metals that would create repulsive and attractive force between them [32]. Hence the main advantage of a single material can be realized by compounding two materials with different properties to produce a bimetallic component. When the performance of one of the materials is high, rare and precious can be replaced to some percentage by combining them with another metal forming the bimetallic components.

While there exist numerous manufacturing methods for producing bimetals, it is essential to subject them to rigorous testing to ensure their suitability as replacements for single metals. Table 2.1 outlines the various testing methods employed to assess the quality of bimetal casts. These methods encompass a range of assessments, including interface bonding, chemical compositions, and mechanical tests, all aimed at scrutinizing the quality of bimetal casts. Some of the common testing methods used for checking the quality of bimetal casts, its interface bonding, chemical compositions, mechanical tests are Optical microscopy (OM), Energy Dispersive X-Ray Spectroscopy (EDS), Scanning Electron Microscope (SEM), Annealing, Microhardness tests, Wear tests, twist tests, Tensile tests, Compression tests etc. While study of the interface bonding has been the major area of research since both metals need to be joined to behave like a single metal. Analysis of images from SEM was one of the most common testing carried out on bimetal studies [5], [7], [13], [24][17]. There are various process parameters that were used by different researchers in order to observe the variations in the microstructure and bonding of the bimetals at the interface. Some of the process parameters were rotational speed of mold[15], [26], [27], preheat temperature of the mold[17][26], first frozen layer temperature[9] , pouring speed of melt [11] , superheat temperature of the melt & cooling rate of the mold during casting[27].

There have been quite a few studies on numerical simulation with the help of softwares like ABAQUS [25], Flow3D[33], ProCAST [34], ANSYS Fluent[35], in order to study the behavior of the flow of melt within the rotating mold. Given that the mold is inherently opaque, visualizing the flow of melt inside it during processes like centrifugal casting can be challenging, if not impossible. It's essential to recognize that the flow of melt significantly impacts the metallurgical bonding of bimetals at the interface, grain formation, microstructure, and ultimately the quality of the resulting cast during the solidification phase.[29]. Since the conditions are dynamic, while the mold is rotating, and the mold is subjected to high temperatures and higher heat transfer rates the analysis becomes complex to understand the flow behavior of the melt. Some researchers have worked on simulating the melt flow experimentally by considering a transparent mold and using different liquids with different viscosity like water[29], oils, glycerin[36], wax[37] etc. Researchers select liquids with varying viscosities because during the initial stages, when molten metal is drawn from the furnace and poured into a rotating mold, it exhibits behavior akin to that of water. As the solidification process progresses, the viscosity of the molten metal gradually increases to higher levels. [38]. This process involves rapid heat loss from the molten metal due to a significant temperature difference between the melt and its surroundings, causing the metal to solidify within a fraction of seconds. Therefore, the study of melt flow becomes a crucial area of investigation, as everything, including mechanical, tribological, thermal, and electrical properties, hinges on the microstructure that develops during the solidification process.

Enhancing the metallurgical bond between the two metals is a critical factor to consider, especially if we intend to utilize bimetals for a wide range of applications in lieu of single metals. The solidification rate plays a pivotal role in shaping both the microstructure [39] and the metallurgical bonding [20]. Higher cooling rates, associated with increased heat transfer rates, can potentially result in metal layers undergoing oxidation during solidification. This oxidation can, in turn, result in subpar metallurgical bonding at the bimetal interface.

Despite the extensive research conducted on bimetal cylinder castings, there remain numerous unexplored avenues for further study, research, and improvement. Specifically, there is a need for research in areas such as enhancing the production of bimetal castings, achieving superior metallurgical bonding at the interface, and minimizing defects in castings. These areas of investigation are closely tied to the various process parameters involved in the casting process.

In-depth research is essential for a comprehensive understanding of these parameters, including the potential for modifying existing ones and introducing new ones. Additionally, leveraging advanced numerical simulations, facilitated by upgraded computers and software, can significantly contribute to the production of high-quality bimetal casts. These advancements hold great promise for various engineering and scientific applications.

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