液固双金属复合铸造及其在汽车轻量化制造中的应用

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摘要：双金属复合铸造将2种成分、性能各异的金属材料制成一个整体铸件，满足零件不同部位难以用单一金属材料达成的性能要求，在汽车制造中实现轻量化。综述了液固双金属复合铸造工艺，分析了双金属界面结合机制与形成条件，总结了表面处理、镶嵌件预热、添加中间层及施加物理场等界面组织与性能调控技术，介绍了铝-铸铁、铝-钢、铝-镁和钢-铸铁双金属复合铸造在汽车轻量化制造中的典型应用及制造工艺，提出了双金属复合铸件的研究方向与发展前景，为双金属复合铸造的研究及其在汽车制造中的应用提供参考。

关键词：双金属　复合铸造　界面调控　汽车轻量化　应用

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Liquid-Solid Bimetallic Compound Casting and Its Applications for Manufacturing Lightweight Automotive Components

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Abstract: Bimetallic compound casting combines 2 metal materials with different compositions and properties into a single integral casting, meeting the performance requirements at different parts of the components that are difficult to achieve with a single metal material, and achieving automotive lightweight. This paper reviews liquid-solid bimetallic compound casting process, analyzes the bonding mechanisms and formation conditions of bimetallic interfaces, and summarizes the interface microstructure and performance control technology such as surface treatment, insert preheating, adding interlayers and application of physical fields, it also presents the typical applications and manufacturing processes of aluminum/cast iron, aluminum/steel, aluminum/magnesium and steel/cast iron bimetallic compound casting in automotive lightweight manufacturing. The paper finally presents the research direction and development prospect of bimetallic compound casting, providing a valuable reference for the research and its application in automotive manufacturing.

Key words: Bimetal, Compound casting, Interfacial regulation, Automotive lightweight, Application

1　前言

现代工业的发展对材料提出了越来越高的要求，单一材料往往难以满足汽车及其他机械零部件的综合性能需求。双金属复合材料可为单个零件的不同部分提供所需的性能，解决单一材料无法完成的要求。双金属复合材料的制备方法有铸造、焊接、挤压、烧结等，其中，铸造复合材料具有工艺过程简单、能一次成形复杂的双金属零件等优点，近年来越来越受到关注[1-4]。

汽车零部件采用多材料结构，在兼顾成本、性能的同时实现轻量化，已经成为汽车用材的趋势[5-6]。多材料结构存在材料之间的连接问题，而双金属复合铸造能将2种或以上不同的金属材料铸造成为一个完整的铸件，在汽车轻量化制造中日益受到重视[7-9]。

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本文介绍双金属复合铸件制造的技术原理、方法,分析双金属界面结合机制,概述双金属界面性能调控技术研究进展,并总结双金属复合铸造在汽车轻量化制造中的典型应用及制造工艺,以期为双金属铸件制造技术及其汽车领域的应用研究提供参考。

2　液固双金属复合铸造工艺与界面调控

2.1　液固双金属复合铸造工艺方法

液固双金属复合铸造是将一种液态金属浇注到已预制好的另一种固体金属上,或将预制好的固体金属浸于金属液中,液态金属凝固后2种金属合为一体,从而形成双金属复合材料铸件。液-固复合也称镶铸(Cast-in Insert)、包覆铸造(Overcasting),通常把预制的固体金属件称为镶嵌件(Insert)。

液固双金属复合铸造通常在传统铸造工艺方法的基础上增加一定的工序实现,其工艺流程因铸件材料、结构、性能要求的差异而不同,如图1所示。复合铸造过程中,首先要预制固态金属件(镶嵌件),镶嵌件需要进行一定的表面处理,包括表面氧化物与油脂清理、表面活化、涂层制备等;铸造时镶嵌件通常要进行预热,其目的是提高基体金属与镶嵌件之间的结合质量、减少收缩应力、防止基体金属收缩开裂。目前,在研究与应用中采用的铸造方法包括砂型铸造[10-11]、金属型重力铸造[12]、低压铸造[13-14]、挤压铸造[15-16]、高压压铸[17-19]、离心铸造[20-21]、消失模铸造[22-23]等,每一种方法都有其特点,其中挤压铸造、高压压铸有利于双金属界面的结合。

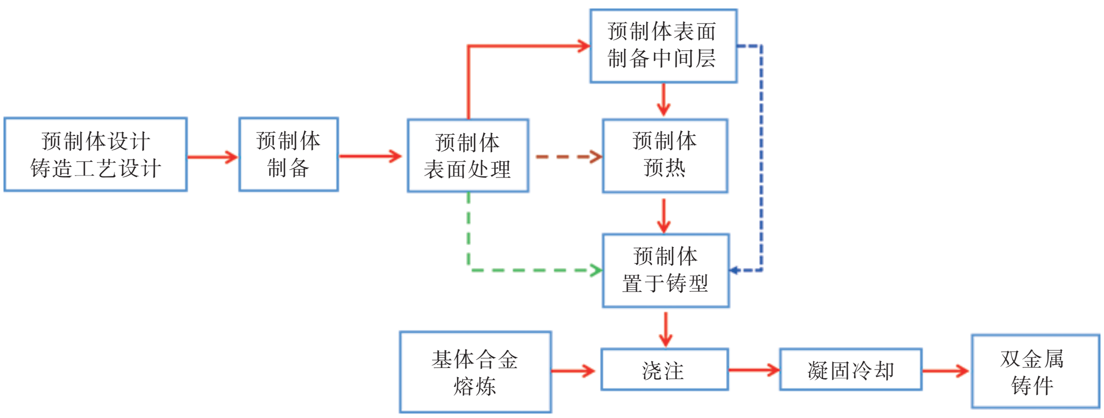


图1　液固复合双金属铸造工艺流程

2.2　双金属复合界面结构与性能调控

液固双金属复合铸造可以实现铸铁-钢[24-25]、铝-铸铁[26-27]、铝-钢[28-29]、镁-铝[30-31]、铝-铜[32-33]、铝-钛[34]、铝-铝[35-36]、镁-钛[37-38]等多种类型金属之间的复合,不同铸造工艺条件下2种金属之间可能形成宏观、微观上不同的结合界面,影响结合强度、导电、导热等性能。因此,2种金属结合界面的设计及界面结构与性能调控是生产高质量双金属复合铸件的关键技术。

2.2.1　界面结合形式及形成条件

液固双金属复合铸件中,2种金属的结合有机械结合与冶金结合2种形式。机械结合是利用镶嵌件周围的液态金属冷却时的收缩力将2种金属连结为一体,2种金属之间没有反应,在显微尺度下2种金属的接触也是不连续的。机械结合界面结合力小,2种金属之间的热阻和电阻大,但生产工艺相对简单。为了提高结合强度,可以在镶嵌件表面上设计、加工一些独特的凸台或凹槽[9,39-41]。

冶金结合是指界面2种金属之间形成了原子结合,按其形成机制可分为2类,即熔合结合与扩散结合[42]。熔合结合是基体金属与镶嵌件熔点接近,基体金属浇注温度较高时,镶嵌件表面会局部熔化并与金属液相混合形成合金,液态金属凝固与镶嵌件形成冶金结合。扩散结合是镶嵌件熔点高,基体金属浇注后不能使其表面熔化,但两者之间能很好润湿,通过扩散作用形成冶金结合。冶金结合的结合强度高,且2种金属之间的热阻和电阻小,因此,在大多数应用中希望获得冶金结合。

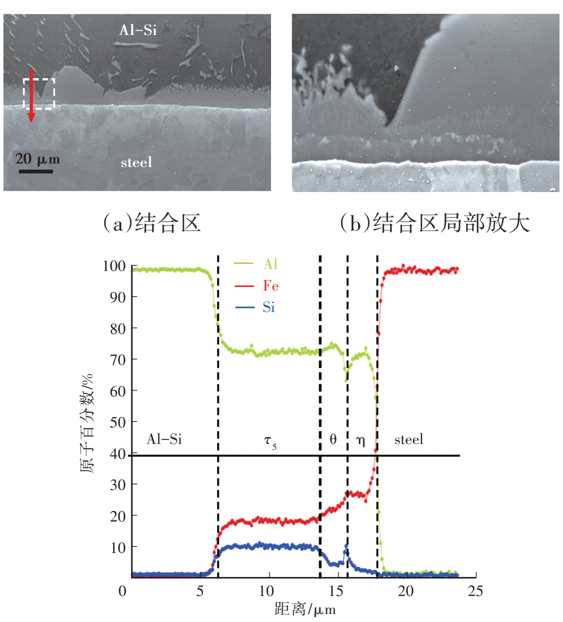
形成冶金结合有2个重要条件:

a. 液态金属与固态金属能够密切接触。要实现两者密切接触，应清洁镶嵌件表面，做到无油污、无氧化膜，油污在高温下会产生气体，并发生碳化而形成碳膜，碳膜和氧化膜都难以被浇注的液态金属破除，它们将阻碍2种金属密切接触，影响冶金结合的形成。

b. 镶嵌件与液态金属有一定的接触时间。固态下原子迁移速度慢，在没有压力的情况下2种固态金属接触时难以形成冶金结合，因此，2种金属接触处需要有液相存在一定的时间。总的时间包括液态金属润湿固态镶嵌件所需要的时间和界面冶金反应所需要的时间，受镶嵌件表面状态、液态金属流动等因素的影响。

2.2.2　界面组织与性能调控

大多数异种金属间的冶金反应会形成金属间化合物，导致双金属复合铸件界面组织中有金属间化合物存在。例如，铝-铁复合时界面处会形成 Al_5Fe_2、$Al_{13}Fe_4$ 等化合物[1,43-44]，铝硅合金与钢复合时还会形成 Al_8Fe_2Si、$Al_{4.5}FeSi$ 等化合物[45]。图2所示为铝硅合金与钢的结合界面的扫描电子显微镜(Scanning Electron Microscope，SEM)图像与其成分X射线光谱(Energy Dispersive Spectrometer，EDS)线扫描结果[45]，可看出界面处存在3层不同的金属间化合物。

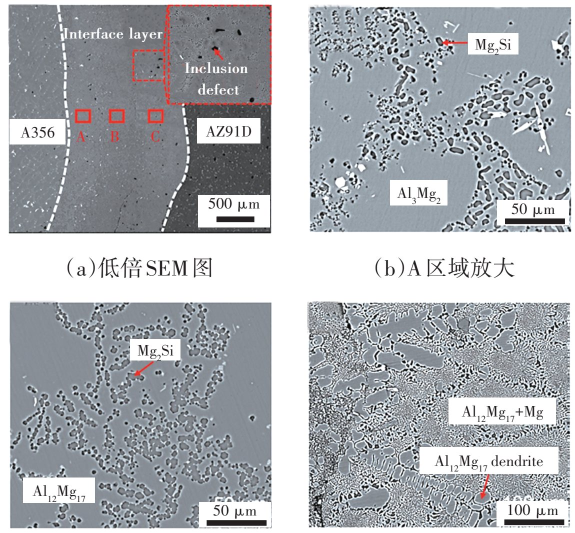


(a)结合区　(b)结合区局部放大

(c)图(2a)中红线成分EDS线扫描

图2　铝硅合金与钢的结合界面SEM图像及其成分EDS线扫描结果[45]

铝-镁复合会形成 Mg_2Al_3、$Mg_{17}Al_{12}$ 等金属间化合物[2,46]，图3是其典型的界面组织。

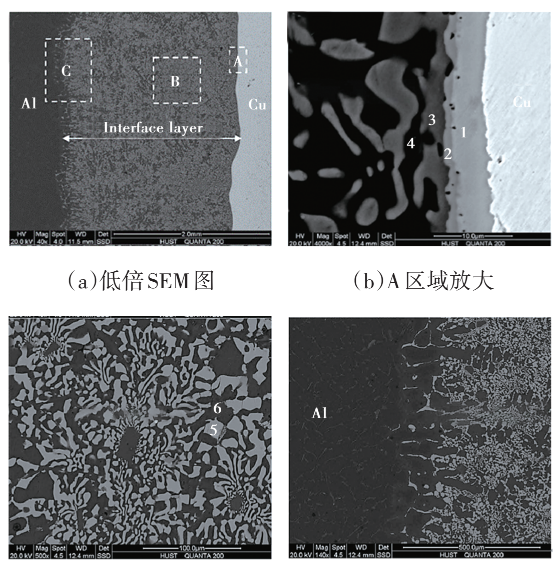


(a)低倍SEM图　(b)A区域放大

(c)B区域放大　(d)C区域放大

图3　铝-镁双金属结合界面SEM图像[46]

铝-铜复合时界面可形成 Al_4Cu_9、AlCu、Al_2Cu 等化合物[47-48]，图4为典型的结合界面SEM图像，图中1、2处分别为 Al_4Cu_9、AlCu，3、5处为 Al_2Cu，4、6处为α-Al[48]。



(a)低倍SEM图　(b)A区域放大

(c)B区域放大　(d)C区域放大

图4　铝-铜双金属结合界面SEM图像[48]

金属间化合物具有硬而脆的特点，影响双金属复合铸件结合界面的力学性能。因此，提高界面性能一方面要提高冶金结合率，另一方面是调控界面物相组成、物相分布及反应层厚度等。国内外对此开展了大量的研究工作，其方法可归纳为表面处理、镶嵌件预热与液态金属过热、添加中

间层、施加物理场等。

a. 表面处理:表面处理包括表面清理和表面活化处理,其主要作用是提高冶金结合率,配合其他工艺参数的调整可调控界面反应层厚度。表面清理可清除镶嵌件表面油脂与氧化膜,提高冶金结合率,这是双金属复合铸造中极为关键的一道工序,所有双金属复合铸造工艺都不能缺少。

表面活化可改变表面原子状态,提高液态金属对固态金属表面的润湿性,从而促进冶金结合界面的形成,减少界面缺陷、改善界面组织。表面活化可分为化学法和机械法。化学法通过一定的化学反应来改变表面原子状态,在铝-铁[49-51]、镁-铝[52]等双金属复合铸造中的研究和应用表明,活化处理明显减少界面缺陷,提高冶金结合率与结合强度。李迟等[49]研究了表面活化处理对铝-钢双金属界面的影响,发现表面活化后界面缝隙率由10.99%降至2.93%,剪切强度提高13.85%。

机械法是采用喷丸、喷砂方法使表面粗化来提高液态金属的润湿性,铝-铁双金属铸造的研究表明,喷丸和喷砂可使界面金属间化合物层厚更薄、更均匀[51,53]。

b. 镶嵌件预热与液态金属过热:根据前述形成冶金结合的第2个条件,镶嵌件与液态金属需要一定的接触时间,这也就是说界面温度需要保持在合金液相线以上一定的时间。界面温度与镶嵌件的预热温度、液态金属的浇注温度有关,镶嵌件预热和液态金属过热温度高,界面的温度越高,保持为液固接触的时间越长。因此,调控镶嵌件预热与液态金属过热温度可以改变冶金反应条件,即可调控界面组织。值得指出的是,影响界面温度的因素还有液固体积比,液固体积比小,液态金属带入的热量少,界面温度保持在液相线温度的时间就短,液固体积比过小难以形成冶金结合[54-56]。

c. 添加中间层:添加中间层是在镶嵌件表面制备金属涂层,其作用可分为两大类:一是防止镶嵌件表面氧化,提高润湿性,促进界面形成冶金结合;二是调整界面组织。

目前,研究及应用的中间层材料很多,有纯金属Sn、Zn、Cu、Ni、Cr等[57-62],也有合金或复合中间层[4,63-65]。制备中间层的方法有电镀[4,58,62,66]、化学镀[33]、热浸镀[67]、喷涂[68-69]等。

Sn、Zn等低熔点金属中间层在复合铸造过程中发生熔化,能增加润湿性,促使界面产生熔合与扩散结合。BAKKE等[57]在研究铝-铜双金属复合铸造时,对铜镶嵌件进行热浸镀Sn,发现Sn中间层显著提高了润湿性,界面抗拉强度最高达到90.8 MPa。

高熔点中间层,如Cu、Ni、Cr等,在复合铸造过程中不发生熔化,通过扩散与浇注的金属形成冶金结合,它们的作用主要是阻止或减少脆性金属间化合物的形成。LIU等[59]研究在铁镶嵌上电镀Cu后进行铝-铁双金属复合铸造,表明Cu中间层能阻止金属间化合物的形成,使界面剪切强度从未添加中间层的31.20 MPa提高到77.65 MPa。

复合中间层中各层的作用不同,例如,在铝—镁复合铸造中采用Ni-Cu复合中间层时,Ni层的作用是阻止Al-Mg金属间化合物形成,Cu层的作用则是与Mg通过扩散形成冶金结合,LI等[66]的研究表明,用电镀方法制备Ni-Cu复合中间层可使A356铝合金-AZ91D镁合金界面结合强度提高20.3%。

d. 施加物理场:在铸造过程中施加振动可以提高双金属界面冶金结合质量,近年来受到了许多关注[70-73]。GUO等[70]、SUI等[71]及LIU等[72]研究超声振动对铝-铁双金属复合铸造的影响,发现超声振动能够改善冶金结合质量,大幅提升其界面结合强度。GUAN等[73]研究超声振动对铝-镁双金属界面组织与性能的影响,发现超声振动消除了界面连续氧化夹杂,细化了组织,结合强度显著提高。GUAN等[74]的研究还发现机械振动也能减少界面氧化物、细化晶粒。

添加磁场也能对液固复合界面的原子扩散行为产生影响,从而调控界面组织与性能。YU等[75]对铝-钢复合铸造的研究表明,添加磁场后界面物相没有变化,但界面处金属间化合物厚度的减少,缓解了变形过程中界面处的应力集中,剪切强度

从(41±7) MPa增加到(56±2) MPa。

对铸型中的镶嵌件进行感应加热也可实现界面组织与性能调控，这种方法在特定条件与需求下有应用前景[76-77]。

3 液固双金属复合铸造在汽车轻量化制造中的应用

双金属复合铸造将2种金属材料连接为一体，满足汽车零部件轻量化或某些特殊性能要求。一些双金属复合铸件已应用于汽车零部件，如发动机缸体、活塞、副车架、制动盘、制动鼓、车身部件中的门框、连接支架等。

3.1 铝(镁)-铁双金属复合铸造

铝、镁的密度小，比强度高，是重要的轻量化金属材料。但是，铝、镁合金的强度比钢铁材料低，特别是其耐磨、耐热性能远不及钢铁材料，将铝(镁)-铁结合制成双金属复合铸件既可实现轻量化，又能满足零部件一些部位的耐磨、耐热性能要求。

铝(镁)-铁双金属复合铸件已在汽车上得到应用，比如，汽车发动机缸体采用铝合金可实现轻量化，但一般铝合金满足不了汽缸对耐磨性、耐热性要求，采用双金属复合铸造技术制备铝-铁双金属复合缸体，如图5所示气缸部分采用铸铁材料，很好地满足了轻量化与性能要求。这种缸体采用压力铸造、低压铸造或重力铸造方法生产，其生产过程一般是将预先制备好的铸铁气缸套除油、除锈，预热至500~580 ℃后放入铸型中，然后合型浇注铝合金液。

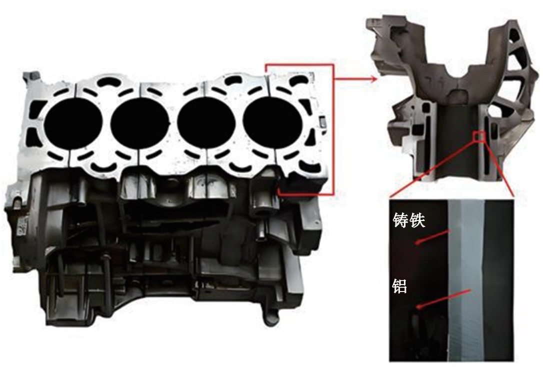
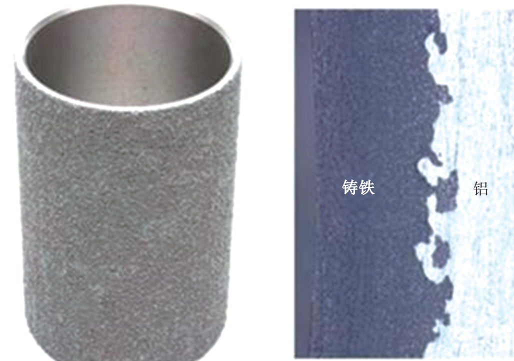
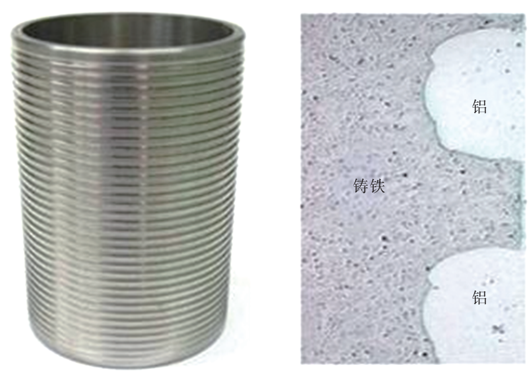


图5 铝-铁双金属复合铸造发动机缸体[27]

为提高铝合金缸体与铸铁缸套的结合质量，铸铁缸套外壁可设计加工出凹槽或凸点，或喷砂使表面粗化，以增加结合面积和机械锁合力，图6所示为铸态粗糙表面及开有螺纹凹槽的缸套表面及其与铝合金结合界面[9]。在缸套外表面采用电镀、热浸镀等方法制备合金中间层[78-79]，可以实现冶金结合，提高铸铁缸套与铝缸体之间的导热性能。高压铸造及工艺优化可使铸铁缸套与铝合金缸体间的气隙减小[14,80]。



(a)铸态粗糙表面



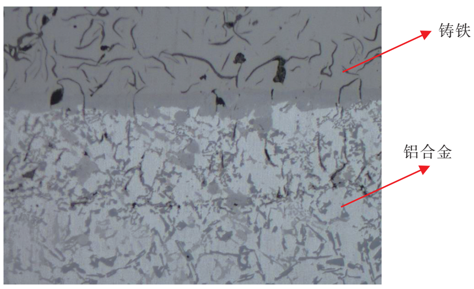
(b)螺纹凹槽表面

图6 铝-铁双金属复合发动机缸体缸套表面及结合界面[9]

汽车发动机活塞通常用铝硅合金整体铸造，大功率发动机 活塞的第一环槽处工作温度高，此时铝合金的耐磨性不能满足要求，故将耐高温、耐磨的铸铁和铝合金结合，在活塞的第一环槽处镶一铁圈，制成铝-铁双金属复合铸造活塞(简称镶圈活塞)，如图7所示。为保证铁圈与铝有相近的热膨胀系数，铁圈采用高镍奥氏体铸铁；为使铁圈与铝基体之间具有良好的导热性和足够的粘结强度，要求铁圈和活塞铝基体之间具有冶金结合，生产上采用超声波检验冶金结合率，一般要求达到85%以上。目前生产上普遍采用Al-fin工艺[81-82]，这种工艺是先将经过表面清理的铁镶嵌件在铝液中浸泡2~5 min，使铝液与铁界面发生扩散反应；

然后将铁镶嵌件从铝液中取出放入铸型,浇注基体金属液,随后基体金属液与镶嵌件表面的铝液熔合、凝固,两者形成冶金结合。

(a)复合铸造活塞



(b)结合界面组织

图7　铝-铁双金属复合发动机缸体缸套表面及结合界面[9]

汽车制动盘一般采用灰口铸铁制造,铝合金的摩擦性能不能满足制动盘的要求。为满足制动盘轻量化需要,可选用铝合金作为盘帽材料,用灰口铸铁作为摩擦环材料,如图8所示。铝合金盘帽与灰口铸铁摩擦环可采用螺栓螺母连接或铆钉连接,也可采用复合铸造技术制成一个整体,以减少盘帽和摩擦环装配工序。复合铸造生产过程中先将已铸造成型的灰铸铁摩擦环放入铸型内,然后浇注铝合金形成盘帽[83-84]。

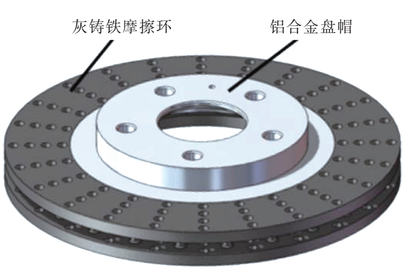


图8　铝-铁双金属复合铸造制动盘

制动鼓也可采用铝-铁双金属复合铸造,制动鼓的内圈采用灰铸铁,外圈采用铝合金,与传统灰铸铁制动鼓比较可减重40%[85]。

近年来人们开始探索将铝-铁双金属复合铸造用于制造承载结构件[86-88], Cosma开发了铝-钢双金属复合铸造发动机托架,BMW研究了铝-钢复合铸造车身纵梁[87],WEIHE等[88]研究了铝-钢复合铸造车顶横梁。

镁-铁双金属复合铸造在汽车上也有应用,例如BMW一款发动机的下缸体采用镁-钢复合铸造,其中钢质镶嵌件作为曲轴轴承[89]。为减轻仪表板横梁的质量,又不显著增加成本,研究人员探索了用镁合金与钢管复合铸造仪表板横梁,如图9所示[7,13]。

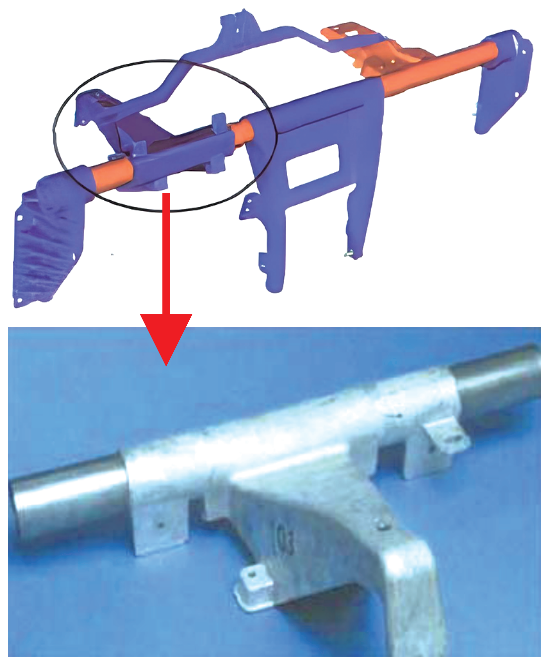
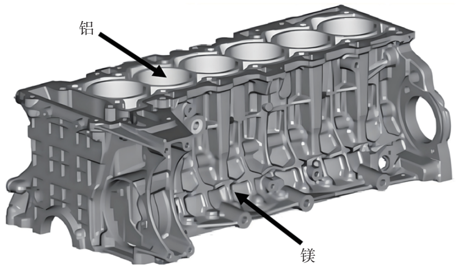


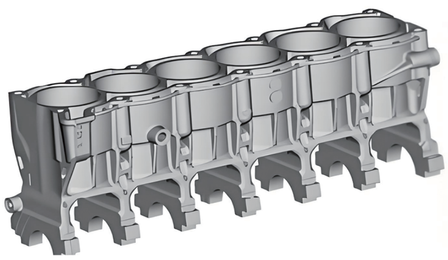
图9　镁-钢双金属复合铸造仪表板横梁[7]

3.2　铝-镁双金属复合铸造

铝与镁都是重要的轻量化金属材料,镁的密度比铝低30%,比强度、比刚度更高,但其耐热性差、蠕变强度低,作为结构件工作温度不能超过120 ℃。因此,铝与镁复合能进一步发挥其轻量化效果,近年来受到许多研究者的关注。BMW率先将铝-镁双金属复合铸造用于生产发动机缸体[89]。在该缸体的材料设计中,考虑到镁合金不适合用于缸筒接触表面和冷却流体通道,采用过共晶铝合金做缸体内衬,镁合金做外壳,如图10所示。生产工艺为:先铸铝合金内衬镶嵌件,其表面用电弧喷涂方法喷一层共晶铝合金,然后采用压铸方法铝合金镶嵌件与镁合金复合。这种铝镁复合缸体比铝合金缸体减重24%(10 kg)。



(a)缸体结构与材料



(b)过共晶铝合金内衬

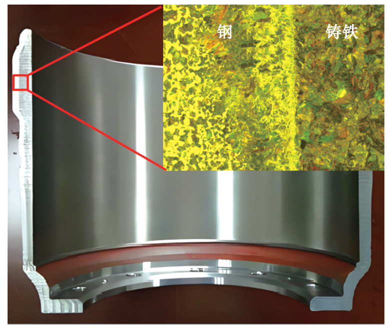
图10　BMW发动机铝-镁双金属缸体[89]

3.3　钢-铸铁复合铸造

钢与铸铁因化学成分、处理工艺不同，性能有很大差异。一般而言，钢的强度高、韧性好，铸铁具有耐磨性好、导热性好、减振性好等特点。将2种不同的钢铁材料用铸造方法结合起来制成双金属复合铸件，既能满足零部件不同部位的性能要求，又可实现轻量化。

钢-铸铁复合铸造在汽车制造中的典型应用是生产重型汽车上的制动鼓[90-91]。钢-铁复合制动鼓采用钢制外壳，内圈是灰铸铁，钢制外壳采用钢板经冲压、旋压成形，再经表面清理、涂刷溶剂、加热烘烤等处理工序，用离心铸造或砂型铸造方法完成钢与灰铸铁的复合，两者形成冶金结合，图11所示为制动鼓及其截面与结合区组织。双金属复合制动鼓比传统灰铁铸造制动鼓质量减轻20%~30%，并能延长制动鼓的使用寿命，增加汽车行驶的安全性[91]。

(a)双金属制动鼓



(b)制动鼓截面与结合区组织

图11　钢-铸铁双金属复合铸造制动鼓

4　结束语

双金属复合铸件可解决单一材料铸件无法满足的综合性能问题，近年来正吸引着越来越多研究者的关注，国内外研究人员在复合工艺、界面组织与性能调控等方面做了大量的研究，在双金属复合铸件的应用上也有很大发展，但还有些问题需要研究：

a. 界面反应及其控制。界面反应形成的微观组织结构决定了2种金属间的结合强度与物理化学性能，因此需进一步研究界面原子扩散行为、界面组织的形成规律，研究表面处理、中间层元素对界面反应与组织形成的影响。

b. 铸造工艺。双金属复合铸造比单一金属铸造的工艺过程复杂，控制要求更高，因此要加强工艺过程数值模拟的研究，优化工艺参数，避免铸造缺陷；另外要研究利用外加超声波、外加磁场等工艺手段来提高界面结合质量、减少界面缺陷。

c. 双金属复合铸件的设计。2种金属通常具有不同的物理性质，铸件成形过程中产生应力、变形的情况更加复杂，因此要研究双金属复合铸件的优化设计方法，铸件在满足轻量化与综合性能要求的同时，考虑减少应力、变形、开裂倾向。

轻量化与高性能是汽车材料及零部件发展的趋势，双金属复合铸造是发展轻量化与高性能复合材料及零部件的重要技术之一。随着该技术的不断完善，将在汽车轻量化与高性能零部件制造中获得越来越广泛的应用。

参考文献：

[1] ROHLWING A, RANE K K, KORDIJAZI A, et al. Cast-

in Inserts, Including MMC Inserts in Aluminum Compound Castings[J]. Transactions of the American Foundrymen's Society, 2022, 130: 57-73.

[2] LI G Y, JING W M, GUAN F, et al. Preparation, Interfacial Regulation and Strengthening of Mg/Al Bimetal Fabricated by Compound Casting: A Review[J]. Journal of Magnesium and Alloys, 2023, 11(9): 3059-3098.

[3] PAPIS K J M, LOEFFLER J F, UGGOWITZER P J. Light Metal Compound Casting[J]. Science in China Series E: Technological Sciences, 2010, 52(4): 46-51.

[4] HAN Q Y. A Modified Cast-on Method for the Reinforcement of Aluminum Castings with Dissimilar Metals[J]. Metallurgical & Materials Transactions B, 2016, 55: 1-8.

[5] 李永兵, 马运五, 楼铭, 等. 轻量化多材料汽车车身连接技术进展[J]. 机械工程学报, 2016, 52(24): 1-23.

[6] BLALA H, PENGZHI C, SHENGLUN Z, et al. Innovative Hybrid High-Pressure Die-Casting Process for Load-Bearing Body-in-White Structural Components[J]. International Journal of Metalcasting, 2024: 18(4): 3460-3481.

[7] LUO A A, SACHDEV A K, POWELL B R. Advanced Casting Technologies for Lightweight Automotive Applications[J]. China Foundry, 2010, 7(4): 463-469.

[8] LUO A A, SACHDEV A K, APELIAN D. Alloy Development and Process Innovations for Light Metals Casting[J]. Journal of Materials Processing Technology, 2022, 306.

[9] SOARES E, REJOWSKI E, MAURIZI M. Cast-in Cylinder Iiners Designs to Improve Bonding and Shear Strength for Aluminum Block[R]. Society of Automotive Engineers, Technical Paper No. 2012-36-0449, 2012.

[10] FANG X, GUNDLACH J, SCHIPPERGES J J, et al. On the Steel-Aluminum Hybrid Casting by Sand Casting[J]. Journal of Materials Engineering and Performance, 2018, 27: 6415-6425.

[11] 陈忠士, 傅高升, 程超增, 等. 双金属汽车刹车毂复合铸造工艺的研究[J]. 铸造, 2012, 61(1): 101-105.

[12] CHEMEZOV D, SMIRNOVA L, BOGOMOLOVA E. Metal Mold Casting of Cast Iron and Aluminium Pistons[J]. ISJ Theoretical & Applied Science, 2018, 61(5): 132-141.

[13] CHIESA F, MORIN G, TOUGAS B, et al. Hybrid Metal Castings-Low Pressure Permanent Pold Overcasting Optimizes Part Characteristics[J]. Modern Casting, 2014, 104(2): 48-55.

[14] 林雪冬, 何弢, 卢建波, 等. 全铝发动机缸套-缸体的成形技术及其导热性能[J]. 特种铸造及有色合金, 2016, 36(4): 345-348.

[15] LIU T, WANG Q, SUI Y, et al. An Investigation into Interface Formation and Mechanical Properties of Aluminum - copper Bimetal by Squeeze Casting[J]. Materials & Design, 2016, 89: 1137-1146.

[16] ALI M A, ISHFAQ K, RAZA M H, et al. Mechanical Characterization of Aged AA2026-AA2026 Overcast Joints Fabricated by Squeeze Casting[J]. The International Journal of Advanced Manufacturing Technology, 2020, 107: 3277-3297.

[17] NOLTE N, LUKASCZYK T, MAYER B. Investigation of the Microstructure and Properties of Aluminum - Copper Compounds Fabricated by the High-Pressure Die Casting Process[J]. Metals, 2022, 12(8): 1314.

[18] WU M, YANG J, HUANG F, et al. Bonding of Cast Iron-Aluminum in Bimetallic Castings by High-pressure Die Casting Process[J]. The International Journal of Advanced Manufacturing Technology, 2022, 120(1): 537-549.

[19] MARTIN S, SULIK D, FANG X F, et al. Steel-Aluminum Hybrid Die Casting: Microstructures Related to the Applied Al-Si Bond Coating[J]. Intermetallics, 2022, 151.

[20] SARVARI M, GHAEMI KHIAVI S, DIVANDARI M, et al. Dissimilar Joining of Al/Mg Light Metals by Centrifugal Compound Casting Process[J]. International Journal of Metalcasting, 2023, 17(2): 998-1007.

[21] GHOLAMI M, GHAEMI KHIAVI S, DEHHAGHI A, et al. Microstructure and Mechanical Properties of the Interface of Aluminum-Brass Bimetals Produced via Vertical Centrifugal Casting (VCC)[J]. International Journal of Metalcasting, 2024, 18(2): 1204-1216.

[22] HEJAZI M M, DIVANDARI M, TAGHADDOS E. Effect of Copper Insert on the Microstructure of Gray Iron Produced via Lost Foam Casting[J]. Materials & Design, 2009, 30(4): 1085-1092.

[23] JIANG W M, LI G Y, FAN Z T, et al. Investigation on the Interface Characteristics of Al/Mg Bimetallic Castings Processed by Lost Foam Casting[J]. Metallurgical & Materials Transactions A, 2016, 47(5): 2462-2470.

[24] 卫振亚, 李光灿. 双金属盘式制动器的试制与研究[J].

铸造技术, 2003, 24(5): 408-410.

[25] HANNA M D, SCHROTH J G, DESSOUKI O S. Bi-Metal Disc Brake Rotor and Method of Manufacturing: US8820491[P].[2014-09-02].

[26] KIM J M, SHIN K, SHIN J S. Microstructural Evolution and Growth of Intermetallic Compounds at the Interface Between Solid Cast Iron and Liquid Al-Si Alloy[J]. Metals, 2020, 10(6): 759.

[27] GUO Z L, LIU M, BIAN X F, et al. An Al-7Si Alloy/Cast Iron Bimetallic Composite with Super-High Shear Strength[J]. Journal of Materials Research and Technology, 2019, 8(3): 3126-3136.

[28] JIANG W M, FAN Z T, LI C. Improved Steel/Aluminum Bonding in Bimetallic Castings by a Compound Casting Process[J]. Journal of Materials Processing Technology, 2015, 226: 25-31.

[29] MOODISPAW M P, CHEN B, LUO A A, et al. Achieving Metallurgical Bonding in Aluminum/Steel Bimetallic Castings[J]. International Journal of Metalcasting, 2024, 18: 2832-2840.

[30] HAJJARI E, DIVANDARI M, RAZAVI S H, et al. Dissimilar Joining of Al/Mg Light Metals by Compound Casting Process[J]. Journal of Materials Science, 2011, 46(20): 6491-6499.

[31] LI G Y, JIANG W M, YANG W C, et al. New Insights into the Characterization and Formation of the Interface of A356/AZ91D Bimetallic Composites Fabricated by Compound Casting[J]. Metallurgical and Materials Transactions A, 2019, 50: 1076-1090.

[32] PINTORE M, WÖLCK J, MITTLER T, et al. Composite Casting and Characterization of Cu-Al Bilayer Compounds[J]. International Journal of Metalcasting, 2020, 14: 155-166.

[33] YUAN H U, CHEN Y Q, LI L I, et al. Microstructure and Properties of Al/Cu Bimetal in Liquid - Solid Compound Casting Process[J]. Transactions of Nonferrous Metals Society of China, 2016, 26(6): 1555-1563.

[34] NIE X Y, LIU J C, LI H X, et al. An Investigation on Bonding Mechanism and Mechanical Properties of Al/Ti Compound Materials Prepared by Insert Moulding[J]. Materials & Design, 2014, 63: 142-150.

[35] SCHWANKL M, WEDLER J, KÖRNER C. Wrought Al-Cast Al Compound Casting Based on Zincate Treatment For Aluminum Wrought Alloy Inserts[J]. Journal of Materials Processing Technology, 2016, 238: 160-168.

[36] RÜBNER M, GÜNZL M, KÖRNER C, et al. Aluminium-aluminium Compound Fabrication by High Pressure Die Casting[J]. Materials Science and Engineering: A, 2011, 528(22/23): 7024-7029.

[37] WEN F L, ZHAO J F, FENG K Q, et al. Investigation of Cu Interlayer on Joint Formation of Ti/Mg Bimetal Fabricated by Liquid - Solid Compound Casting Process[J]. Metals and Materials International, 2022, 28(7): 1711-1724.

[38] CHENG J, ZHAO J H, WANG C, et al. Effect of HEA/Al Composite Interlayer on Microstructure and Mechanical Property of Ti/Mg Bimetal Composite by Solid-liquid Compound Casting[J]. China Foundry, 2023, 20(1): 1-11.

[39] KODAMA H, FUKUMOTO T. Cast-Iron Insert and Method of Manufacturing Same: US7226667[P]. [2007-06-05].

[40] BRUCKMEIER L, RINGEL A, VROOMEN U, et al. Influence of High-Pressure Die Casting Process Parameters on the Compound Strength of Hybrid Components with Undercut Sheet Metal[J]. Metals, 2023, 13(10): 1717.

[41] HORIGOME M, SAITO G.Cylinder Liner for Insert Casting Use: US9089893[P]. [2015-07-28].

[42] 刘耀辉, 刘海峰, 于思荣. 液固结合双金属复合材料界面研究[J]. 机械工程学报, 2000, 36(7): 81-85.

[43] BAKKE A O, ARNBERG L, LØLAND J O, et al. Formation and Evolution of the Interfacial Structure in Al/Steel Compound Castings During Solidification and Heat Treatment[J]. Journal of Alloys and Compounds, 2020, 849.

[44] VIALA J C, PERONNET M, BARBEAU F, et al. Interface Chemistry in Aluminium Alloy Castings Reinforced with Iron Base Inserts[J]. Composites Part A: Applied Science & Manufacturing, 2002, 33(10): 1417-1420.

[45] SPRINGER H, KOSTKA A, PAYTON E J, et al. On the Formation and Growth of Intermetallic Phases During Interdiffusion Between Low-Carbon Steel and Aluminum Alloys[J]. Acta Materialia, 2011, 59(4): 1586-1600.

[46] HAJJARI E, DIVANDARI M, RAZAVI S H, et al. Intermetallic Compounds and Antiphase Domains in Al/Mg Compound Casting[J]. Intermetallics, 2012, 23: 182-186.

[47] AHMADZADEH SALOUT S, MIRBAGHERI S M H. Mi-

crostructural and Mechanical Characterization of Al/Cu Interface in a Bimetallic Composite Produced by Compound Casting[J]. Scientific Reports, 2024, 14(1): 7529.

[48] JIANG W M, GUAN F, LI G, et al. Processing of Al/Cu Bimetal Bia a Novel Compound Casting Method[J]. Materials and Manufacturing Processes, 2019, 34(9): 1016-1025.

[49] 李迟, 樊自田, 蒋文明, 等.表面处理对钢/铝双金属铸件组织性能的影响[J].特种铸造及有色合金, 2015, 35(05): 516-519.

[50] 张元好, 曾大新, 张红霞, 等. 铸铁镶圈活塞活化渗铝工艺及其活化处理设备: 201410024492.8[P]. 2014, 2014-05-28.

[51] SUN L, LI C A, TU J W, et al. Effect of Surface Treatment to Inserted Ring on Al-Fe Bonding Layer of Aluminium Piston with Reinforced Cast Iron Ring[J]. Journal of Central South University, 2014, 21(8): 3037-3042.

[52] ZHANG H, CHEN Y Q, LUO A A. A Novel Aluminum Surface Treatment for Improved Bonding in Magnesium/Aluminum Bimetallic Castings[J]. Scripta Materialia, 2014, 86: 52-55.

[53] SHIN J, KIM T, LIM K, et al. Effects of Steel Type and Sandblasting Pretreatment on the Solid-liquid Compound Casting Characteristics of Zinc-coated Steel/Aluminum Bimetals[J]. Journal of Alloys and Compounds, 2019, 778: 170-185.

[54] SARVARI M, DIVANDARI M, SAGHAFIAN H, et al. Effect of Melt-to-solid Volume Ratio and Preheating Temperature on Mg/Al Bimetals Interface by Centrifugal Casting[J]. China Foundry, 2023, 20(3): 234-240.

[55] JIANG W M, FAN Z T, Li G Y, et al. Effects of Melt-to-solid Insert Volume Ratio on the Microstructures and Mechanical Properties of Al/Mg Bimetallic Castings Produced by Lost Foam Casting[J]. Metallurgical and Materials Transactions A, 2016, 47(12): 6487-6497.

[56] LIU G P, WANG Q D, ZHANG L, et al. Effects of Melt-to-solid Volume Ratio and Pouring Temperature on Microstructures and Mechanical Properties of Cu/Al Bimetals in Compound Casting Process[J]. Metallurgical and Materials Transactions A, 2019, 50: 401-414.

[57] BAKKE A O, ARNBERG L, LI Y J. Achieving High-Strength Metallurgical Bonding Between A356 Aluminum and Copper Through Compound Casting[J]. Materials Science and Engineering: A, 2021, 810: 140979.

[58] TAVAKOLI A M, NAMI B, MALEKAN M, et al. Influences of Coating Type on Microstructure and Strength of Aluminum-steel Bimetal Composite Interface[J]. International Journal of Metalcasting, 2022, 16(2): 689-698.

[59] LIU S Y, XU H, ZHANG B H, et al. The Effect of the Cu Interlayer on the Interfacial Microstructure and Mechanical Properties of Al/Fe Bimetal by Compound Casting[J]. Materials, 2023, 16(15): 5469.

[60] FENG J, YE B, ZUO L J, et al. Bonding of Aluminum Alloys in Compound Casting[J]. Metallurgical & Materials Transactions A, 2017, 48(10):4632-4644.

[61] WEN K, ZHANG G W, ZHANG Z C, et al. Enhanced Bonding Strength of Al/Fe Bimetal by Ni-based Interlayer Prepared by Laser Cladding Technique[J]. Materials Today Communications, 2024, 38: 107906.

[62] ZHANG D, ZHANG G W, YU H, et al. Controlling Interfacial Composition and Improvement in Bonding Strength of Compound Casted Al/Steel Bimetal Via Cr Interlayer[J]. Journal of Materials Research and Technology, 2023, 23: 4385-4395.

[63] ZHAO J H, ZHANG Y Q, HE J S, et al. Interfacial Microstructure in Joining of Arc Sprayed Al-Zn Coating to AZ91D by Solid-liquid Compound Casting[J]. Surface and Coatings Technology, 2016, 307: 301-307.

[64] 陈达, 陈翌庆, 徐光晨, 等. ZL109/Q235液-固复合工艺及其界面组织性能[J].特种铸造及有色合金, 2013, 33(7):665-668.

[65] SUI D, CHEN Y C, HAN Q Y. Reducing Macroscopic Defects at the Aluminum/Steel Interface in Bimetal Castings Made by the Cummins Process[J]. Metallurgical and Materials Transactions B, 2023, 54(3): 1483-1498.

[66] LI G Y, JIANG W M, GUAN F, et al. Microstructure, Mechanical Properties and Corrosion Resistance of A356 Aluminum/AZ91D Magnesium Bimetal Prepared by a Compound Casting Combined with a Novel Ni-Cu Composite Interlayer[J]. Journal of Materials Processing Technology, 2021, 288: 116874.

[67] JIANG W M, JIANG H X, LI G Y, et al. Microstructure, Mechanical Properties and Fracture Behavior of Magnesium/Steel Bimetal Using Compound Casting Assisted with Hot-dip Aluminizing[J]. Metals and Materials International, 2021, 27: 2977-2988.

[68] HE K, ZHAO J H, LI P, et al. Investigation on Micro-Structures and Properties of Arc-sprayed-Al/AZ91D Bimetallic Material by Solid - liquid Compound Casting[J]. Materials & Design, 2016, 112:553-564.

[69] CHENG J, ZHAO J H, ZHENG D Z, et al. Investigation on the Microstructure and Mechanical Properties of Arc-spray-coated Q235/AZ91D by Solid-liquid Compound casting[J]. International Journal of Metalcasting, 2020, 14: 518-527.

[70] GUO R, ZENG D X, LI F G. Promoting of Metallurgical Bonding by Ultrasonic Insert Process in Steel - aluminum Bimetallic Castings[J]. High Temperature Materials and Processes, 2022, 41(1): 289-295.

[71] SUI D, HAN Q Y. Ultrasound-assisted Cast-on Method: Obtaining High-quality Metallurgical Bonds Between A Bare Steel Insert and A354 Aluminum Alloy Within a Composite Casting[J]. Journal of Materials Processing Technology, 2023, 311: 117783.

[72] LIU X T, SUI D, SUN D, et al. Ultrasonic Cast Bonding of Sheet Steel to Aluminum in A Metal Mold[J]. International Journal of Metalcasting, 2024, 18: 3496 - 3505.

[73] GUAN F, JIANG W M, WANG J L, et al. Development of High Strength Mg/Al Bimetal by A Novel Ultrasonic Vibration Aided Compound Casting Process[J]. Journal of Materials Processing Technology, 2022, 300: 117441.

[74] GUAN F, JIANG W M, LI G Y, et al. Effect of Vibration on Interfacial Microstructure and Mechanical Properties of Mg/Al Bimetal Prepared by A Novel Compound Casting[J]. Journal of Magnesium and Alloys, 2022, 10(8): 2296-2309.

[75] YU H, ZHANG G W, LV W Z, et al. Improved Microstructure and Shear Strength of the Al/Steel Bimetal Prepared by Compound Casting under Magnetic Field[J]. Journal of Alloys and Compounds, 2023, 932: 167343.

[76] LOCKE C, GUGGEMOS M, MAIER L, et al. Hybrid Joining of Cast Aluminum and Sheet Steel Through Compound Sand Casting and Induction Heating to Enable thin-walled Lightweight Structures[J]. Journal of Materials Processing Technology, 2024, 324: 118261.

[77] LOCKE C, PICHLER R, GUGGEMOS M, et al. Expanding Lightweight Design Potential by Hybrid Joining of Aluminum Sheets with Aluminum Casting through Compound Sand Casting and Induction Heating[J]. Advanced Engineering Materials, 2024, 26(21): 2400549.

[78] KAMYAB M, HAJIALIMOHAMMADI A, MOTALEBI S, et al. Investigating the Effect of the Coating Process on Improving the Quality of Mechanical Bonding in the Casting of Aluminum Cylinder Block with Cast-in Iron Liner[J]. The Journal of Engine Research, 2023, 70(2): 80-98.

[79] REJOWSKI E, DE SOUZA J P, RABELLO R B. New Coated Cast-In Liner to Improve Heat Transfer on Aluminum Blocks[R]. SAE Technical Paper, 2016, 2016-36-0262.

[80] BALACHANDAR D, NATARAJ N. Process Improvements to Reduce Bonding Gap between Aluminum Cylinder Block and Cast-In Liner and Evaluation through Non-Destructive Techniques[R]. SAE Technical Paper, 2023, 2023-01-0880.

[81] SZWAJKA K, ZIELIŃSKA-SZWAJKA J, TRZEPIECIŃSKI T. Influence of the Duration and Temperature of the Al-Fin Process for the Cast Iron Insert on the Microstructure of the Bimetallic Joint Obtained in the Piston Casting Process[J]. Metals, 2023, 13(5): 897.

[82] MANASIJEVIĆ S, RADIŠA R, BRODARAC Z Z, et al. Al-Fin Bond in Aluminum Piston Alloy & Austenitic Cast Iron Insert[J]. International Journal of Metalcasting, 2015, 9: 27-32.

[83] KIM Y C, KIM S J, LEE J, et al. Improvement of Manufacturing and Evaluation Technology for the Light Weight Brake Disc Composed of Hybrid Type Material [R]. SAE Technical Paper, 2014, 2014-01-1009.

[84] KIM Y C , HAN J M , RHEE Y J ,et al. Method of Manufacturing Brake Disc of Heterogeneous Materials and Brake Disc of Heterogeneous Materials Manufactured Using the Same:US10598237. 2020-3-24.

[85] RAJ S, SHANKAR S R. Design and Development of Bimetal Brake Drum to Improve Heat Dissipation and Weight Reduction[R]. SAE Technical Paper, 2014, 2014-01-2284.

[86] SENFF M, VOLK W. Hybrid Joining of Cast Aluminum and Steel by Compound Casting and Friction Stir Welding[J]. Production Engineering, 2023, 17(3): 521-534.

[87] LEHMHUS D, VON HEHL A, HAUSMANN J, et al. New Materials and Processes for Transport Applications: Going Hybrid and Beyond[J]. Advanced Engineering Materials, 2019, 21(6).

[88] WEIHE S, ERNST A, RÖTH T, et al. Aluminium-Steel Composite Casting in Commercial Vehicle Manufacturing[J]. ATZ Worldwide, 2013, 115(4): 52-56.

[89] HOESCHL M, WAGENER W, WOLF J. BMW's Magnesium-Aluminium Composite Crankcase, State-of-the-Art Light Metal Casting and Manufacturing[J]. SAE Technical Paper, 2006-01-0069, 2006.

[90] 宋军. 重型汽车双金属制动鼓的旋压成型与离心浇铸复合成型技术研究[D]. 镇江: 江苏大学, 2017.

[91] 河南恒久制动系统有限公司. 产品技术[EB/OL]. (2025-01-09) [2025-03-13]. http://www. hengjiumech. com/ Composite.html.

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