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球墨铸铁研磨盘试制

石磊¹,汪强¹,徐建国¹,付向上¹,曾豪峰¹,吕振林²

(1. 江西铜业集团(德兴)铸造有限公司,江西 德兴 334224; 2. 西安理工大学 材料科学与工程学院,陕西 西安 710048)

摘要:依据研磨盘的技术要求,采取无冒口、明发热冒口、暗发热冒口和壳型+铁模+发热冒口等铸造工艺方法试制了球墨铸铁研磨盘。结果表明,无冒口、明发热冒口和暗发热冒口的工艺方法均无法消除球墨铸铁研磨盘表面及内部的缩松缺陷。而壳型+铁模配合发热冒口设置的工艺方法可有效消除球墨铸铁研磨盘表面及内部的缩松缺陷,研磨盘加工表面光洁,退火后硬度 161~165 HB,满足研磨盘使用的技术要求。

关键词:球墨铸铁;研磨盘;铸造工艺

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Trial Production of Ductile Iron Grinding Discs

SHI Lei¹, WANG Qiang¹, XU Jianguo¹, FU Xiangshang¹, ZENG Haofeng¹, LYU Zhenlin²

(1. Jiangxi Copper Group (Dexing) Foundry Co., Ltd., Dexing 334224, China; 2. School of Materials and Engineering, Xi'an University of Technology, Xi'an 710048, China)

Abstract: On the basis of the technical requirements of grinding discs, a ductile iron grinding disc was produced via various casting processes, such as no riser, an open riser and a closed riser with an exothermic feeder sleeve and a shell + iron mold combined with an exothermic feeder sleeve. The results show that neither the process method without risers nor the process methods with open risers or closed risers can eliminate the shrinkage porosity defects on the surface and inside of the ductile iron grinding disc. The shell mold + iron mold process combined with an exothermic feeder sleeve can effectively eliminate shrinkage porosity defects both on the surface and inside the grinding plate. The grinding plate has a smooth processing surface and hardness of 161~165 HB after tempering, which can meet the technical requirements for the use of the grinding plate.

Key words: ductile iron; grinding disc; foundry process

在半导体制造领域,晶圆研磨机起着至关重要的作用,其通过多级研磨工艺和化学机械抛光技术,可以有效去除晶圆表面的不均匀性和缺陷,达到晶圆所需的厚度和平整度要求,为后续的半导体制造提供高质量的晶圆基底^[1-6]。作为晶圆研磨机及其研磨工艺的关键部件,研磨盘技术指标直接决定了晶圆的研磨质量和效率。研磨盘的技术要求主要涵盖:优异的平面度稳定性、耐磨性、组织和性能均匀性、磨料镶嵌性和耐腐蚀性。尽管晶圆研磨盘有多种材质^[7-10],但对于大尺寸晶圆研磨盘而言,铸铁材料还是当前的主流选择之一^[11-12],尤其是铁素体球墨铸铁更符合其技术要求。基于此,江西铜业集团(德兴)铸造公司应某公司的要求,开展了球墨

铸铁研磨盘的试制,旨在研发出符合晶圆研磨技术要求的研磨盘,以满足晶圆研磨加工的性能和质量需求。

1 球墨铸铁研磨盘技术要求

球墨铸铁研磨盘形状为圆环盘状,外径 1 140~2 160 mm,内径 350~730 mm,厚度 50~65 mm,共 4 种型号,其中最大的研磨盘尺寸为外径 2 160 mm、内径 730 mm、厚度 60 mm,单重约 1 441 kg。要求硬度 160~180 HB,表面及内部无气孔、缩孔、缩松、砂眼、夹渣等铸造缺陷。根据研磨盘硬度要求,选用 QT400-15 为研磨盘材料,其化学成分如表 1 所示。

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作者简介: 石磊,1994 年生,学士,助理工程师,主要从事耐磨铸件的生产和技术管理方面的工作。Email: 1575866581@qq.com

通信作者: 吕振林,1963 年生,博士,教授,研究方向为金属耐磨材料的研究与开发。Email: 695794269@qq.com

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表1 球墨铸铁研磨盘成分

Tab.1 Composition of the ductile iron grinding disc
(mass fraction/%)

C	Si	Mn	P	S	Mg	Re
3.6~3.7	2.2~2.5	0.2~0.35	<0.03	<0.015	0.04~0.05	0.03~0.05

2 球墨铸铁研磨盘的试制

最大研磨盘相当于大平板类铸件。基于研磨盘的形状和球墨铸铁的凝固特性,研究团队分别选择了无冒口铸造、有冒口铸造及壳型+铁模配合发热冒口铸造,开展了外径 2 160 mm 的最大尺寸研磨盘试制工作,并依据各铸造方法设计了铸造工艺。

2.1 无冒口铸造

由于球墨铸铁凝固时产生较大的石墨化膨胀,为无冒口铸造提供了条件^[13-15]。采用树脂砂型,内圈底箱进水,研磨盘顶面均匀设置 8 个 $\phi 30$ mm 的出气孔(图 1a)。然而开箱落砂后球墨铸铁研磨盘上表面发生严重的缩凹,如图 1b 所示。球墨铸铁的凝固属于糊状凝固,石墨球在奥氏体壳包围下生长(离异共晶),碳原子的移动速度受到限制,生长速度慢,难以使金属液形成坚实的外壳,此时如果封闭外壳的壳内局部金属液收缩而形成真空空间,且在高温下外壳强度不足,承载能力差,金属液补充不足时会在大气压力的作用下,外壳塌陷形成缩凹^[16-17]。

为解决球墨铸铁研磨盘上表面的缩凹缺陷,研究团队设计了内圈盖箱进水无冒口铸造工艺。该工艺在研磨盘上表面均匀布置了 8 个 $\phi 30$ mm 出气孔,开箱落砂后的研磨盘如图 2a 所示,表面切削加工去除 3 mm 后(首道工序采用表面刮平 1 刀,后续表面切削加工每刀切削量 3~5 mm),其表面可见明显缩松痕迹,如图 2b 白圈区域。

随后又设计了外圈盖箱进水无冒口铸造工艺,同样在上表面设置 8 个出气孔,浇注后的研磨盘如图 3a 所示。然而打磨清砂后发现,研磨盘表面仍有缩凹,如图 3b 所示。研磨盘上表面车削 2 刀,去除 9 mm 以后,表面还有少量缩松存在,如图 3c 所示。

上述 3 种铸造工艺试验表明,大尺寸球墨铸铁研磨盘不适合采用无冒口铸造。

2.2 有冒口铸造

发热冒口可以强化冒口的补缩效果,并减小冒口的尺寸和重量,能够有效解决铸件的缩孔、缩松缺陷^[18-21]。为消除大尺寸球墨铸铁研磨盘内的缩松缺陷,在研磨盘上表面设计均布了 6 个 $\phi 180$ mm $\times$ 300 mm 的明、暗 2 种形式发热冒口进行试制。

实施明发热冒口工艺并采用内圈底箱进水浇注方案后,清理所得的研磨盘宏观形貌如图 4a 所示。经机械加工后,冒口根部附近表面出现明显花斑(图 4b)。花斑的显现,表明研磨盘内部仍为不致密组织

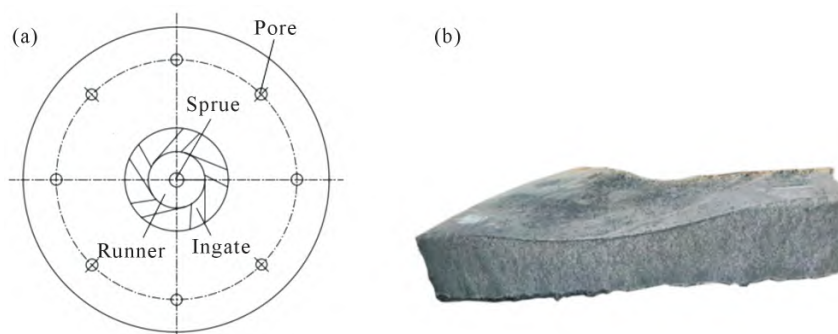


图 1 无冒口内圈底箱进水浇注研磨盘:(a) 工艺示意图;(b) 研磨盘表面缩凹宏观形貌

Fig.1 Molten iron ingress into the drag flask of the inner ring without risers for pouring the grinding disc: (a) process schematic diagram; (b) surface depression of the grinding disc

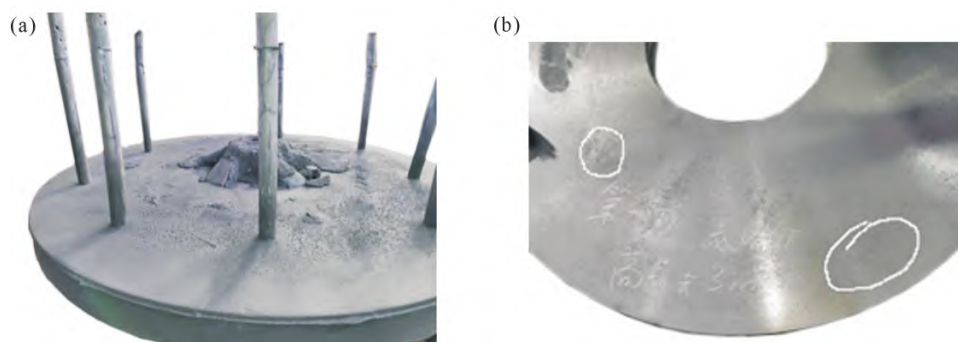


图 2 无冒口内圈盖箱进水浇注研磨盘:(a) 落砂后研磨盘形貌;(b) 表面切削 3 mm 后形貌

Fig.2 Molten iron ingress into the cope flask of the inner ring without a riser for pouring the grinding disc: (a) morphology of the grinding disc after shake-out; (b) morphology after surface cutting by 3 mm



图3 无冒口外圈盖箱进水浇注的研磨盘:(a)落砂后研磨盘形貌;(b)清理后磨盘表面形貌;(c)表面切削2刀去除9 mm后的形貌

Fig.3 Molten iron ingress into the cope flask of the outer ring without risers for pouring grinding discs: (a) morphology of the grinding disc after shake-out; (b) surface appearance of the grinding disc after cleaning; (c) morphology after surface cutting with two passes to remove 9 mm

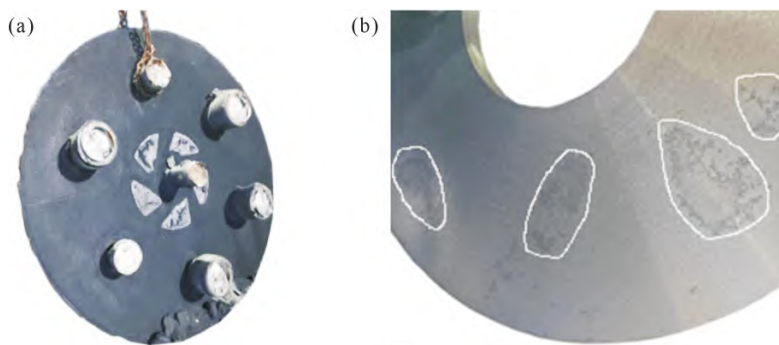


图4 明发热冒口内圈底箱进水浇注的研磨盘:(a)落砂后的研磨盘;(b)表面加工后的研磨盘形貌

Fig.4 Molten iron ingress into the drag flask of the inner ring with an open exothermic feeder sleeve for pouring the grinding disc: (a) grinding disc after shake-out; (b) surface morphology of the grinding disc after machining

或者出现异常石墨。这种现象说明冒口根部铁液过热较大,凝固较慢,从而引起缩松或异常石墨的出现^[22-23]。

在明发热冒口不能完全消除研磨盘内部缩松的状况下,研究团队又设计了暗发热冒口、内圈底箱进水及靠近冒口附近放置排气孔,如图5a所示。然而铸造后的研磨盘表面切削5刀去除17 mm后开始出现缩松,至第8刀去除29 mm后缩松区域面积最大(图5b),表明暗发热冒口可以消除一定厚度的缩松,但在研磨盘厚度中心还存在一定的缩松缺陷。

由此可见,虽然设置了明、暗两种形式的发热冒口,有利于减轻大尺寸球墨铸铁研磨盘的缩松程

度,但还没有完全消除其内部的缩松缺陷。

2.3 壳型铁模铸造

基于上述几种铸造工艺措施均未彻底消除大尺寸球墨铸铁研磨盘内部的缩松缺陷,研究团队设计了壳型+铁模+发热冒口的工艺和内圈盖箱进水的浇注系统。将预制的壳型(石英砂+树脂,热芯盒射砂成型)组装在铁模中(底箱),增强球墨铸铁在铸型中的冷却速度^[24],盖箱采用树脂砂型。在发热冒口的强力补缩和铁模强制冷却条件下消除研磨盘缩松缺陷。其中冒口增加到18个,分内外两圈布置,内圈6个均布在 $\phi 1\ 000\text{ mm}$ 的圆周上;外圈12个均布在 $\phi 1\ 750\text{ mm}$ 的圆周上,如图6a所示。冒口采用的是福

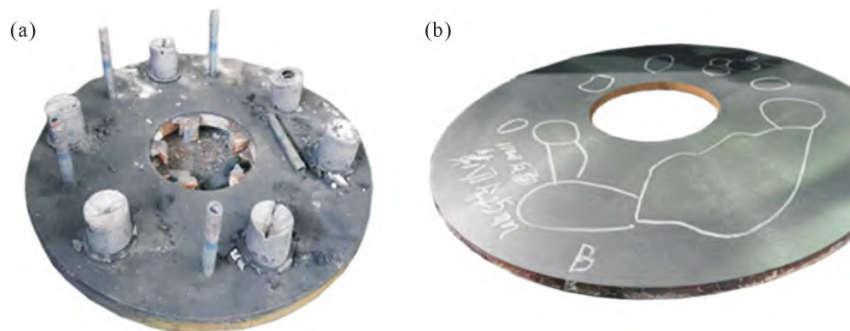


图5 暗发热冒口内圈底箱进水浇注的研磨盘:(a)落砂后的研磨盘;(b)研磨盘表面切削29 mm后的形貌

Fig.5 Molten iron ingress into the drag flask of the inner ring with a blind exothermic feeder sleeve for pouring the grinding disc: (a) grinding disc after shake-out; (b) morphology of the grinding disc after cutting 29 mm from the surface

士科 VSK770 带金属易割片的发热保温冒口 ($\phi 80\text{ mm} \times 180\text{ mm}$)。研磨盘质量约 1 800 kg(含冒口和加工余量)。壳型与铁模组合如图 6b 所示,根据传热学关系计算了铁液凝固过程中的冷却速度,并参考文献[25]的结果,确定了铁模底面厚度为 75 mm,壳型厚度为 20 mm。

对壳型+铁模配合发热冒口铸造后的大尺寸球墨铸铁研磨盘进行机加工切削,切削表面光洁,没有任何铸造缺陷,如图 7 所示。

3 球墨铸铁研磨盘的组织与硬度

采用壳型+铁模+发热冒口工艺铸造的大尺寸球墨铸铁研磨盘,其铸态表面车光后的硬度分布经 HL-600 型里氏便携式硬度计测试(结果折算成布氏

硬度),如图 8 所示。数据表明,研磨盘径向的硬度分布较为均匀,硬度最低点为 175 HB(仅有一点,推测与该部位铁素体含量偏多,珠光体含量偏低有关),最高点为 213 HB,36 个硬度点的平均值为 197.5 HB。其铸态组织由铁素体+珠光体+球状石墨组成(图 9a)。经退火处理后,显微组织主要由铁素体+球状石墨组成,仅存少量的珠光体(图 9b),此时研磨盘的硬度为 161~165 HB,平均硬度 162.2 HB,符合球墨铸铁研磨盘的硬度要求。

4 结论

(1)无冒口和有冒口铸造的球墨铸铁研磨盘均无法消除其表面及内部的缩松缺陷。而壳型+铁模配合发热冒口铸造的球墨铸铁研磨盘,加工后表面

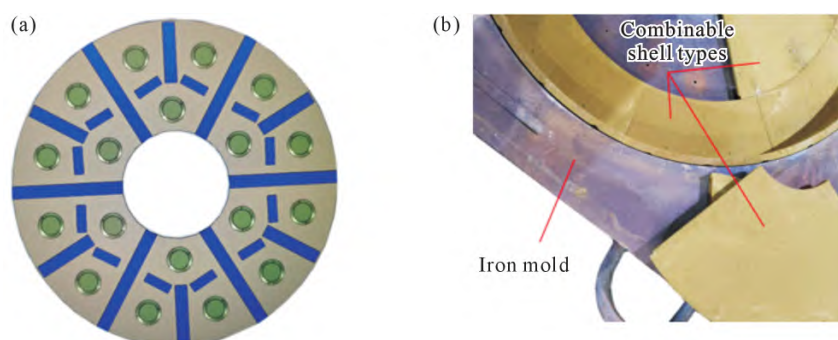


图 6 壳型+铁模组合和发热冒口布置图:(a) 发热冒口布置图;(b) 壳型与铁模组合图

Fig.6 Layout of the shell mold + iron mold with an exothermic feeder sleeve: (a) layout of the exothermic feeder sleeve; (b) combined diagram of the shell mold and iron mold

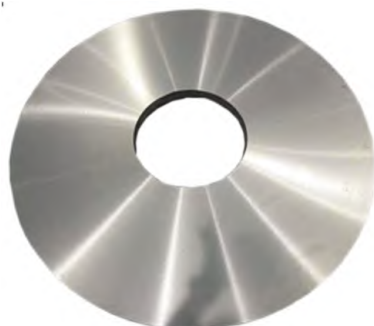


图 7 壳型+铁模铸造的研磨盘切削后形貌

Fig.7 Morphology of the grinding disc produced by shell mold + iron mold casting after machining

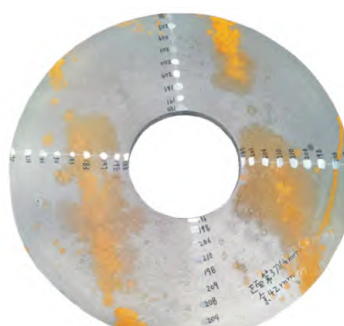


图 8 壳型+铁模铸造的研磨盘铸态硬度

Fig.8 As-cast hardness of the grinding disc produced by shell mold + iron mold casting

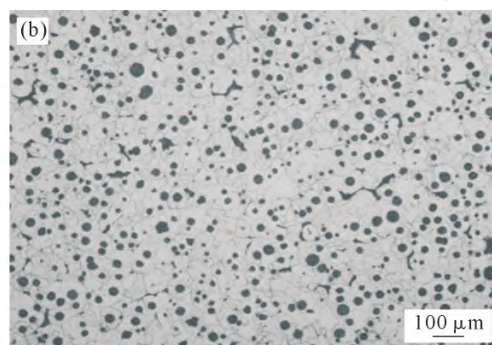
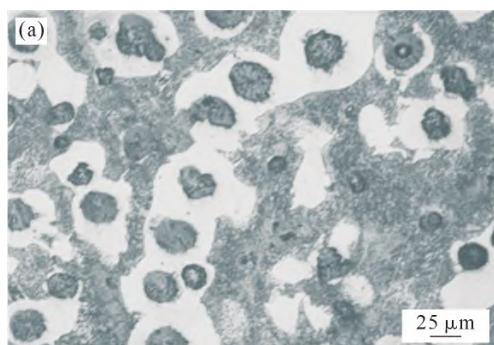


图 9 壳型+铁模和发热冒口铸造的球墨铸铁研磨盘金相组织:(a) 铸态组织;(b) 退火态组织

Fig.9 Metallographic structure of the ductile iron grinding disc produced by the shell mold + iron mold with an exothermic feeder sleeve: (a) as-cast microstructure; (b) annealed microstructure

光洁,没有缩凹、缩松等铸造缺陷。

(2)退火后组织为铁素体+球状石墨及少量的珠光体,硬度为161~165 HB。

(3)试制结果表明,壳型+铁模配合发热冒口铸造的球墨铸铁研磨盘质量和硬度完全满足研磨盘的技术要求,已具备工程化批量生产条件,为大尺寸球墨铸铁研磨盘的工业化生产提供了可行的技术方案。

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