Direct Pour Vs. Traditional Gating

A study comparing direct pouring and traditional gating for an aluminum blade showed direct pouring increases yield and improves costs and mold making.

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直接浇注和传统浇注工艺比较

通过对铝合金叶片直接浇注和传统浇注工艺的比较，研究表明：直接浇注不仅增加了产出率，还优化了成本和砂型制造。

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Due to its generous hydraulic basins, more than 90% of electricity in Quebec, Canada, is produced by water turbines. However, numerous sites cannot be economically, technically or environmentally developed using conventional hydropower technologies (i.e., hydroelectric dams). Novel low power water turbines are sought to suit shallow, high flow rivers; they would be particularly effective in remote areas where they could replace fuel powered generators.

Each propeller for a 15kW water turbine uses five cast aluminum blades fixed to its axle. The Centre de Métallurgie du Québec, Trois-Rivières, Québec, Canada, was tasked with providing the technology to produce cast blades, meeting stringent conditions on as-cast surface finish (≤250 rms) and geometry (±2 mm [0.08 in.]) of the theoretical envelope (Fig. 1). Plus, 140MPa minimum yield strength and 2% elongation were required in the highest stressed parts of the blade.

Aluminum alloy A356 (AlSi7Mg04) was selected for its availability and excellent castability. It also exhibits good corrosion resistance when immersed in fresh river water. As

由于丰富的水力资源，加拿大魁北克地区90%以上的电力来自水力发电。然而，很多使用常规水电技术（即水电坝）的发电站不能产生很好的经济效益，技术效益和环保效益。因此，研发新型低功耗的水轮机来适应低水位、高流量的河流；这样的水轮机尤其对偏远地区十分实用，可以替代燃料驱动的发电机。

每台15 kW的水轮机螺旋桨由5个铸铝叶片固定在轮轴上。加拿大魁北克Trois-Rivières市的魁北克金属研究中心受委托提供叶片的铸造技术，需满足铸件表面光洁度（≤250 rms）和外部几何尺寸（±2 mm [0.08 in.]）的严格要求（图1）。同时，叶片承受最大压力的部分需满足140MPa的最小屈服强度和2%的延伸率。

铝合金A356（AlSi7Mg04）以其可用性和优良的铸造性能被选定为铸造材料。在清澈的河水中，它显示出

Table 1. Tensile Properties Inside the T6 Treated Blade
表1： T6测试中的叶片拉伸性能

	Yield Strength (MPa) 屈服强度（MPA）	Ultimate Tensile Strength (MPa) 最终拉伸强度(MPa)	Elongation (%) 延伸率	Quality Index (MPa) 质量指数
L1	199	232	2.3	285
L2	-	-	-	-
L3	203	228	2.2	279
L4	205	231	3	303
L5	209	250	3.1	323
C1	202	236	2.3	289
C2	207	224	2.1	272
C3	228	250	2.1	299
C4	214	248	3.3	325
R1	204	236	2.4	291
R2	224	248	2.1	295
R3	228	252	2.2	303
E1	201	250	2.9	319

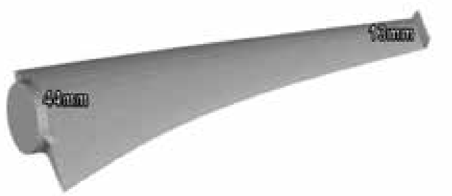

Fig. 1. The 20.2-lb. (9.1 kg) aluminum A356 water turbine blade is 36.6 in. (930 mm) long, with thickness ranging from 1.7 in. (44 mm) to 0.5 in. (13 mm).

图1：20.2磅（9.1千克）的A356铝合金水轮机叶片长度为36.6英寸（930毫米），厚度从1.7英寸（44毫米）至0.5英寸（13毫米）。

for the casting process, the Centre de Métallurgie du Québec examined two methods for production—sand casting using traditional gating and sand casting with the direct pour method. If the metallurgical properties were found to be similar for the two filling procedures, direct pour technology would make the molding much easier in a smaller flask while increasing the yield and eliminating finishing costs.

In their study, the researchers compared the optimal operational parameters, such as pouring temperature and pouring time, for both methods. Metallurgical properties, including dendrite fineness (secondary dentrite arm spacing) and microporosity along with tensile properties, were measured at 13 locations.

Traditional Gating vs. Direct Pour Mold Filling

The wedge-shaped aluminum blade is a perfect geometry for casting, as solidification smoothly progresses from the thin end of the part to the thick extremity, providing self-feeding as long as a riser is placed at the hot end of the blade. The traditional rigging is shown in Fig. 2. It included a sprue, sprue well with a filter at the parting line, two runners and six gates corresponding to an unpressurized gating ratio of 1:2:4 with a resulting filling time of 25 seconds. The yield was 70%.

The cup of a direct pour system combines a ceramic foam filter held inside an insulating ceramic sleeve (see inset in Fig. 3). The assembly acts as a pouring cup, filter and riser, allowing the metal to be poured directly into the mold cavity, eliminating the traditional sprue-runner-gate system. It considerably simplifies the molding process and promotes directional solidification since the hottest metal is poured

良好的耐腐蚀性。在铸造工艺方面，魁北克金属研究中心对两种生产工艺进行了检验——传统浇注砂型铸造和直接浇注砂型铸造。结果表明，如果两种浇注工艺的冶金性能相似，直接浇注工艺在较小砂箱中的成形更加容易，同时提高了产量、节省了加工费用。

研究人员比较了二者最佳的运行参数，如浇注温度和浇注时间。他们还测量了13个点的冶金特性，包括枝晶细度（二次枝晶间隙）和显微疏松，以及拉伸性能。

传统浇注与直接浇注工艺对比

楔形铸铝叶片是完美的几何形状，因为只需在叶片的热端放置冒口就可以完成自动给料，叶片从薄的一端到厚的一端的凝固过程可以顺畅进行。如图2所示，传统的浇注系统包含一个浇口，浇口和过滤片位于叶片一侧，2个浇道和6个横浇道，所对应的非承压的浇注比为1：2：4，充型时间25秒。产出率是70%。

直接浇注系统的浇口杯含有置于绝缘陶瓷套筒内的泡沫陶瓷过滤器（见插图3）。该组件充当了浇口杯、过滤片和冒口，使金属液直接浇入模腔中，取代了传统浇口杯–直浇道-横浇道的浇注系统。温度最高的金属液被浇入到冒口，大大简化了模塑过程并促进了定向凝固。直接浇注尤其适合于叶片铸造，因为过滤器下面的金属液滴大小适中（2 in. [50 mm]）。

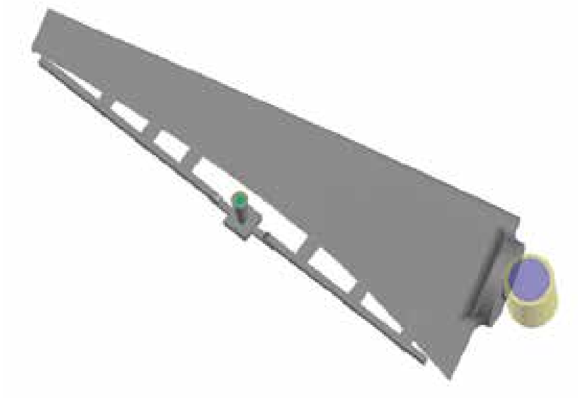

Fig. 2. A conventional sprue-runner-gate system is shown.

图2：直浇口-横浇道-内浇口的传统浇注系统

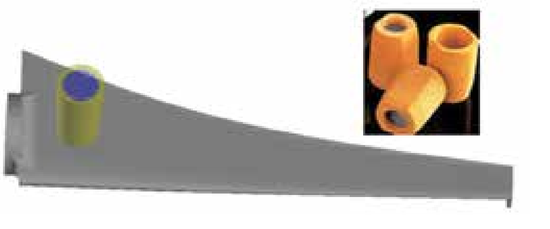

Fig. 3. In direct pour filling, the metal is poured through a ceramic filter directly into the mold cavity via pouring cups (shown in inset).

图3：采用直接浇注充型工艺，金属液通过浇注杯的陶瓷过滤器直接浇入型腔进行充型（见插图）。

Table 2. Tensile Properties Solutionizing at 450C (842F)
表2：450C (842F)固溶状态的拉伸性能

	Yield Strength (MPa) 屈服强度（MPA）	Ultimate Tensile Strength (MPa) 最终拉伸强度(MPa)	Elongation (%) 延伸率	Quality Index (MPa) 质量指数
L1	155	189	2.5	249
L2	154	186	2.05	233
L3	159	192	2.35	247
L4	161	195	3.5	277
L5	163	201	4.1	293
C1	162	199	2.2	251
C2	158	177	1.9	218
C3	161	193	2.1	241
C4	168	197	3.2	272
R1	170	194	2.25	247
R2	165	191	2.25	244
R3	165	193	2.15	243
E1	165	189	2.25	242

into the riser. Direct pour is particularly suited to the blade because the liquid metal drop under the filter is moderate (2 in. [50 mm]).

Comparisons

The pouring temperature was adjusted so the predicted temperature of the liquid metal front during filling would never reach a temperature below the liquidus temperature of aluminum A356 (1,135F [613C]). A pouring temperature of 1,364F (740C) with a 25-second fill time was set for the conventional gating, and a corresponding temperature of 1,274F (690C) with a 10-second fill time was set for the direct pour arrangement.

Filling with the conventional gating is shown in Fig. 4; a corresponding sketch for the direct pour filling is shown in Fig. 5. These two modeled fillings show conventional gating loses more superheat during filling due to heat losses in the runners and gates and due to its slower pouring rate.

The direct poured blade solidified slightly faster because of the lower pouring temperature. The thin edge of the blades solidified in about two minutes, while the

比较

通过调节浇注温度，金属液在充型过程中的预测温度不会低于铝A356的液相线温度（1,135F[613℃]）。传统的浇注系统充型时间是25秒，浇注温度为1,364F（740℃），而直接浇注的充型时间为10秒，相应的浇注温度为1,274F（690℃）。

图4为传统浇注系统充型时的模拟图，图 5是直接浇注的模拟图。这两个模拟图表明，传统浇注系统在充型中因其在浇道中产生热损失和较慢的充型速率而损失更多的热量。

由于浇注温度较低，直接浇注的叶片凝固速度略快。叶片的薄边大约在两分钟内凝固，而铸件的厚端在20分钟内凝固。

铸件在L，C和E位置的微观结构比较（如图6所示）。枝晶间隙在这三个位置几乎是相同的;但是：

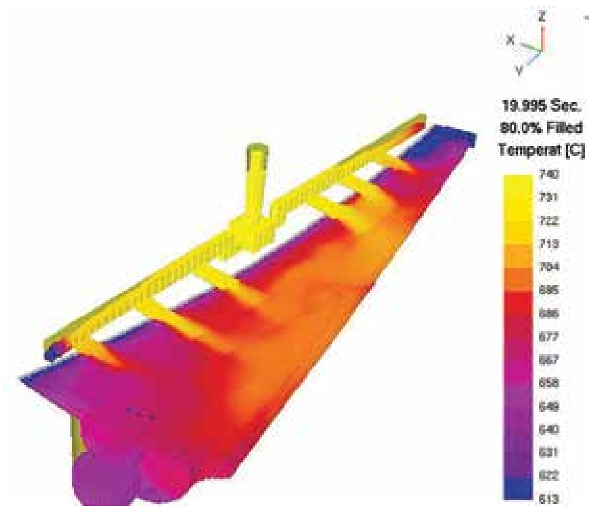

Fig. 4. Modeled filling with the conventional gating is illustrated.
图4：传统浇注系统充型模拟图

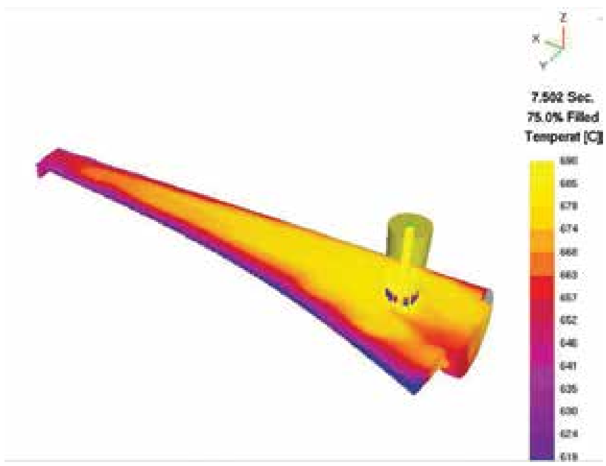

Fig. 5. Modeled filling using the direct pour cup is illustrated.
图5：直接浇注系统充型模拟图

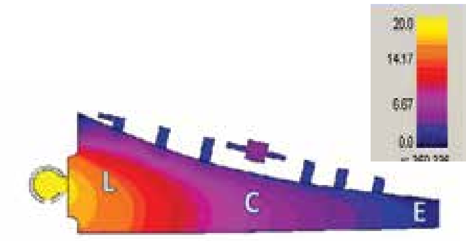

Fig. 6. Solidification sequence for conventional gating is illustrated (time in minutes).

图6：传统浇注系统的凝固顺序（时间：分）

thick end of the casting solidified in 20 minutes.

Microstructures of the castings were compared at locations L, C and E (indicated in Fig. 6). Dendrite arm spacing was virtually the same at the three locations; however:

In the thick section (L) of the casting, the level of microporosity is less in the conventionally gated blade (0.44% vs. 0.88%).

In the thin section of the casting, the level of microporosity is less in the direct poured blade (0.19% vs. 0.25%).

No significant differences in the metallurgical quality of the gated and direct poured blades were noticed in spite of the much lower pouring temperature used with the direct pour technology.

The blades were given a standard T6 heat treatment consisting of solutionizing for 12 hours at 1,000F (538C), followed by quenching in 149F (65C) water and aging for six hours at 320F (160C).

Thirteen tensile test bars were excised from the blades at locations shown in Fig. 7.

The yield strength, ultimate tensile strength and elongation at break appear in Table 1, along with the Quality Index (Q), which represents the metallurgical quality of the alloy.

The yield strength does not vary much around a value of 200 MPa. However, the ultimate tensile strength and elongation are higher in the thinner parts of the blade where the solidification time is lower. The quality index is less than 316 MPa, the minimum value of Q required for the ASTM B26 standard tensile specimen. This is explained by the fact that the 0.5-in. diameter standard specimen solidifies in about one minute while the solidification time in the blade varies from two to 20 minutes.

Heat Treatment and Modified Heat Treatment

Distortion from the quenching process was evaluated by measuring the shift at certain coordinates. This distortion should be reduced as much as possible. Since the mechanical properties in the blades exceeded the requirements (YS ≥140 MPa, El ≥ 2%), the researchers reduced the solutionizing temperature from 1,000F (538C) to 842F (450C).

The modified heat treatment reduced distortion consid-

在铸件的厚壁部分（L），传统浇注叶片的显微疏松水平较低（0.44% vs. 0.88%）。

在铸件的薄壁部分，直接浇注叶片的显微疏松水平较低（0.19% vs. 0.25%）。

尽管直接浇注方式的浇注温度低得多，传统浇注方式或直接浇注方式叶片的冶金质量没有明显差异。

叶片一般需经过标准的T6热处理，包括在1000°F（538°C）下12小时的固溶处理，随后在149F（65°C）的水中淬火和在320°F（160°C）下6小时的时效处理。

13根拉伸试棒从叶片上取样位置如图7所示。

屈服强度、极限抗拉强度和断裂延伸率，以及代表合金冶金质量的质量指数（Q），见表1。

屈服强度在约200MPa时变化不大。然而，叶片较薄部分的凝固时间较短，因此最终的拉伸强度和延伸率较高。其质量指数低于316MPa，这是ASTM B26标准拉伸试样所需的最小质量指数。事实证明，直径为0.5英寸的标准试样凝固时间约为1分钟，而叶片不同部位的凝固时间在2到20分钟。

热处理和改进热处理

淬火过程中的变形通过测量特定坐标的位移来评估，应尽可能减少这样的变形。由于叶片的机械性能超过了需求（屈服强度≥140 MPa，延伸率≥2%），研究者将固溶温度从1000°F（538°C）降低到842°F（450°C）。

改进后的热处理工艺极大的减少了变形；然而，必须对机械性能仍然超过规定的最小值进行验证。

叶片经改进工艺的热处理后，质量指数下降约50 MPa，但是屈服强度和延伸率仍然高于所需的最低

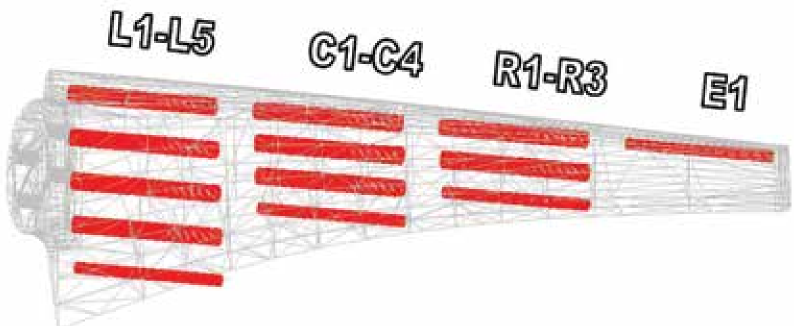

Fig. 7. The sketch shows the location of test bars excised in the blade.

图7：从叶片上取下来的测试棒的位置图

Fig. 8. Filling with direct pour from the side is illustrated.

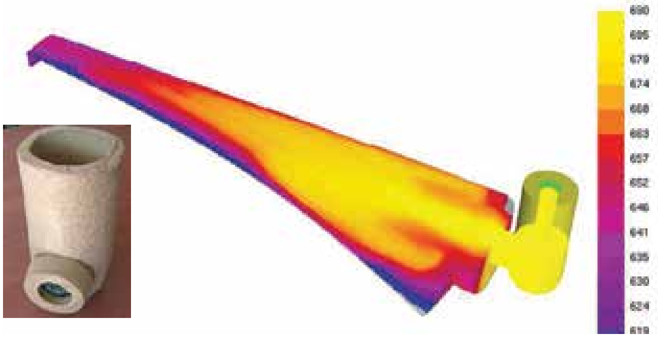

图8：侧边直接浇注充型图

erably; however, it had to be verified that the mechanical properties still exceeded the minimum values specified.

After the modified heat treatment was applied to a blade, the quality index dropped by about 50 MPa, but the yield strength and elongation remained above the minimum required, particularly the yield strength (Table 2). The yield strength varied from 154 to 170 MPa, while the minimum required was 140 MPa. These properties by far exceeded the yield strength of an as-cast blade as previously determined by mechanical testing. The modified mild heat treatment more than doubled the yield strength of the as-cast blade.

Side Fill Direct Pour

In order to avoid a rough finish on the blade's surface, the direct pour cup was modified to fill the cavity by the side rather than from the top (Fig. 8). This arrangement avoided the grinding of the blade surface at the cup-casting connection and provided a less turbulent liquid metal flow into the mold cavity. The surfaces receiving the hydrokinetic energy were smooth, as-cast shapes providing optimum hydrodynamic efficiency for the water turbine (Fig. 9).

The direct pour filter cup technology studied on the blade highlighted the main advantages of direct pour:

1. Lower metal pouring temperature—1,274F (690C) vs. 1,364F (740C).
2. Simpler molding operation and a reduction of 25% in sand usage.
3. Lower finishing costs and a near net shape as-cast product, especially when using filling from the side.
4. Improved yield, from 70% to 85%.
5. Reduced distortion in the as-cast condition as the fast-cooling runners and gates pull on the solidifying casting when the conventional rigging is used. ■

This article is based on paper 14-003 presented at the 2014 AFS Metalcasting Congress.

值，尤其是屈服强度（表2）。屈服强度在154-170 MPa之间，而所需的最低值为140 MPa，超过了铸造叶片先前通过机械测试确定的屈服强度。改进的温和热处理工艺使铸态叶片的屈服强度变为之前的两倍多。

侧边直接浇注

为了避免叶片的表面粗糙，直接浇注的浇口杯改为开在侧边而不是在顶部（图8）。这样的设计避免了浇口杯和铸件连接处叶片表面的打磨，而且使液态金属充型时紊流更小。叶片在水力作用下表面变得光滑，这样的铸态形状使水轮机发挥最佳的水力效率（图9）。

采用直接浇注及过滤杯技术对叶片进行的研究突出了直接浇注的主要优点：

1.降低了金属液的浇注温度，从1,364℉（740℃）降低到1,274℉（690℃）。

2.简化了造型作业，减少25%的砂子使用。

3.降低了清理成本且得到近净形的铸态产品，尤其是改为侧边充型后。

4.产出率从70%提高至85%。

5.减少铸造时的变形，采用传统浇注系统时，由于直浇道和横浇道的快速冷却影响了凝固中的铸件形态。■

本文出自2014年美国铸造协会铸造大会上发表的14-003号论文。

Fig. 9. Two faces of a blade filled from the side are pictured.

图9：侧边浇注叶片的两面