Cast aluminum alloys have been successful in a variety of powertrain components in high performance motorcycles (Fig. 1). An example is the water-cooled, 250 cm³ cylinder block (Fig. 2) manufactured by vacuum assisted high-pressure die-casting (HPDC). In this process, liquid metal is ladled into the shot sleeve of the 800-ton horizontal die-casting machine and injected into the water-cooled die, where it rapidly solidifies under hydraulic pressure of approximately 80 MPa. The time from the onset of liquid metal injection to the completion of die filling is approximately 1.5 seconds. The cylinder block is ejected from the mold when its temperature is below solidus (approximately 380°C), and it undergoes further post-processing operations. If properly applied, vacuum HPDC technology renders an improved casting structure, as well as better mechanical and functional characteristics.

This motorcycle cylinder block has a monolithic, liner-less bore surface. To withstand severe operational conditions during engine operation, it is made of a hypereutectic Al-Si alloy (DiASil). Typically, in addition to containing about 20% silicon, this alloy also contains copper (~3%) and magnesium (~0.5%) to increase the alloy hardness and strength in the heat treated condition via precipitation of Cu₂Al and Mg₂Si phases. Additionally, phosphorus (~0.01%) is added to help achieve uniform size, shape, and distribution of the primary silicon crystals nucleated by AlP₃ particles during solidification.

This cylinder-block alloy has a good combination of wear resistance, thermal conductivity, and low density. In particular, the higher silicon concentration (~4% more than the conventional 390 alloy) minimizes thermal expansion while raising thermal conductivity, thus improving engine cooling performance. Tests on the actual engine revealed that the bore-wall surface temperature decreased by 30°C, and oil consumption was reduced by half compared with the cast-iron lined aluminum cylinder.

The tribological properties of the block are mainly controlled by the primary silicon crystal size, distribution, and exposure height from the aluminum matrix. Hardness of the heat treated cylinder block is predominantly determined by the volume fraction of pri-
mary and eutectic silicon phases in addition to the hardness of the aluminum matrix, which is controlled largely by Cu and Mg via precipitation strengthening.

Conventional HPDC components are not easily solution-treated because of air entrapment during rapid mold filling, resulting in blistering. Application of a vacuum in the range of 250 mbar during HPDC processing minimizes gas content and allows for high-temperature solution treatment, resulting in further improvement of the mechanical properties. A properly designed heat treatment should increase cylinder block hardness and contribute to improved wear resistance while maintaining the casting cost at a competitive level. The conventional T6C heat treatment for this cylinder block consists of solution treatment at 490°C for four hours followed by water quenching and artificial aging at 200°C for four hours. Overall, the T6C duration of approximately nine hours represents up to 97% of the total engine manufacturing cycle. Figure 3 shows that the T6C temper contributes significantly to the casting manufacturing costs.

**Current Standards**

Existing heat treatment standards were designed predominantly for sand castings having coarse microstructure characteristics from slow cooling rates (<5°C/s). Quite often, they are blindly applied to components that do not require extensive thermal processing, such as vacuum HPDC. Rapid cylinder block solidification during the HPDC operation results in a finer microstructure and elevated solute content in the as-cast condition. Consequently, these castings do not require long solution times for the effective dissolution of intermetallic phases and the adequate thermal modification of structural constituents. The typical estimated cylinder-block solidification rate varies between 50 and 85°C/sec, depending on the casting wall thickness.

Figure 4 shows the size of the primary silicon crystals as well as secondary dendrite arm spacing (SDAS) as a function of solidification rate obtained from the advanced laboratory casting experiments. The typical solidification rates achievable for sand castings (SC) and low and high pressure die casting processes (LPPM, HPDC) are shown for reference purposes.

Development of energy-efficient heat treatment processing is crucial for this motorcycle cylinder block to ensure its improved in-service performance while maintaining manufacturing costs at a competitive level.

**Short-Cycle T6 Tempers**

Heat-treatment optimization studies consisted of both laboratory and industrial experiments. They demonstrated the possibility for process time reduction of up to 70% compared with conventional processing for the vacuum HPDC engine blocks (T6M vs. T6C). The table presents relevant details pertaining to evaluated tempers. According to Yamaha Motor Co. Ltd.

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**SELECTED PARAMETERS OF MODIFIED AND CONVENTIONAL TEMPERATURES FOR DIASIL(a)**

<table>
<thead>
<tr>
<th></th>
<th>Direct hot transfer, °C</th>
<th>Solution</th>
<th>Aging</th>
<th>Hardness, HRB</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6C</td>
<td>25</td>
<td>490</td>
<td>4</td>
<td>200</td>
<td>2/10(b)</td>
</tr>
<tr>
<td>T6M</td>
<td>380</td>
<td>510</td>
<td>0.5</td>
<td>200</td>
<td>2/55(b)</td>
</tr>
</tbody>
</table>

(a) Hypereutectic Al-Si alloy. (b) Includes heating time to solution/aging operations.
engineering specifications, macrohardness is a quality indicator of the cylinder block, because it relates to the cylinder’s tribological characteristics. Therefore, the target hardness of >73 HRB (Buehler Rockwell Tester; B scale 100-kg load) can serve as an indicator of the effectiveness of the heat treatment, and consequently cylinder block acceptance criteria.

A revised T6M temper resulted in a hardness of 77.2 HRB, which is 3.7 divisions higher than the conventional T6C temper for the vacuum HPDC engine blocks (HRB = 73.5). The total process duration for the conventional T6C temper is 9 hours, 10 min, while the modified T6M temper’s total duration is 2 hours, 55 min. Tensile testing confirmed that for both of the tempers analyzed, it is feasible to maintain comparable mechanical properties (i.e., ~260MPa UTS) as shown in Fig. 5.

Satisfactory improvement of the mechanical properties and a 70% reduction of the heat treatment duration were achievable due to the following factors:

- Increase in solution treatment temperature from 490 to 510°C
- Reduced solution time at 510°C from 4 to 0.5 hr
- Reduced artificial aging time at 200°C from 4 to 2 hr
- Casting “direct hot transfer” to solution treatment operation

Physical Metallurgy

Cylinder-block rapid solidification resulted in significant thermal microstructure modification and elevated as-cast mechanical properties. It also produced a beneficial structure for subsequent energy-efficient heat treatment processing. The small SDAS of the cylinder block varied between 5 and 14 μm (for thick and thin sections, respectively), and a well-refined Al-Si eutectic reduced the microstructure homogenization time during the T6M temper as a result of the reduced diffusion distances.

Optimization of the solution treatment temperature (i.e., 510°C) maximized the effectiveness of the T6M temper. The exact determination of the alloy’s melting temperature was based on the thermal analysis heating curve, which minimized the risk of incipient melting and improved the dissolution kinetics of the copper- and magnesium-base phases. In turn, this led to a process time reduction. To reduce the processing time, it was crucial to perform solution treatment at a maximum but safe temperature to avoid incipient melting. The hardness after the solution treatment at 510°C was increased due to the elevated solid solubility of the Cu-, Mg-, and Si-base phases in the aluminum matrix.

Close integration of the cylinder block solidification process with the solution treatment (i.e., direct hot transfer) allowed for additional processing time reduction. This type of direct hot transfer arrests the post-ejection cooling temperature at 380°C. Therefore, both the time and energy necessary to reheat the component to the solution treatment temperature were eliminated.
Industrial implementation of direct hot transfer could impose significant practical challenges without changing industrial standards and redesigning the existing equipment. The degree of direct hot transfer temperature depends on how quickly the casting can be transferred to the heat treatment furnace. In addition to accelerating the production rate (higher output), the mechanical properties of the casting were improved while process duration was significantly reduced.

Rising energy costs should become a positive stimulus to revise existing heat treatment standards. Particularly, cast components that have high solidification rates (during HPDC processing) should be carefully analyzed to take advantage of the thermal as-cast microstructure modification and its effect on the response of casting to subsequent heat treatment processing. In the long term, such R&D activities will lead to the replacement of long heat treatment cycles, and therefore should enhance energy efficiency. The expected benefits include less energy-intensive processing as well as more efficient manufacturing, allowing for wider application of light alloys and consequent component weight reduction.

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