EFFECT OF HIGH THERMAL CONDUCTIVITY DIE STEEL IN ALUMINUM CASTING

M. Ayabe, T. Nagaoka, Honda Motor Co., Ltd., Suzuka, Mie, Japan

K. Shibata, H. Nozute, Honda Motor Co., Ltd., Ozu-machi Kikuchi-gun, Kumamoto, Japan

H. Koyama, Honda Engineering Co., Ltd., Haga-gun, Tochigi, Japan

K. Ozaki, T. Yanagisawa, Daido Steel Co., Ltd., Nagoya, Aichi, Japan

Abstract

Recently, the application of aluminum die cast parts in automobile manufacturing has increased because of the greater demand for automotive weight reduction. For even wider application, it is necessary to reduce manufacturing costs and improve product quality. A material possessing a thermal conductivity 50% higher than the conventional 5% chromium hot work tool steel, AISI-H13, was developed as a die material for high- and low-pressure die casting machines.

In this research, the product cooling rate for dies using this type of steel was faster than with the conventional steel, and it was hypothesized that cycle time may be shortened and product cost reduced. A ferrous material with high thermal conductivity, HDS-1, was developed for application to die casting dies. Thus, HDS-1 was used to produce a water jacket core of an engine block die for a high-pressure die casting machine and the cylinder head upper die of a low-pressure die casting machine. The result was a reduced die surface temperature, with the faster cooling rate verified through analysis of the microstructures of the die-cast parts. The results of test application of these dies using the high thermal conductivity material suggest that it is possible to improve tool service life and casting quality simultaneously.

Keywords: *thermal conductivity, die steel, soldering, heat check, secondary dendrite arm spacing (SDAS).*

Introduction

In recent years, aluminum die cast parts—that is, the engine block, transmission casing, and wheels, among others—have widely been used in the automotive industry to reduce vehicle weight. Accompanying the increasing need for further weight reduction, there is a need for broader applications. Reducing manufacturing costs and improving the quality of diecastings is critical in further promoting the use of aluminum die cast components. The production volume of aluminum diecastings for use in automobiles has grown larger with increases in the production volume of overall automobile manufacturing. Additionally, the applications are expanding to frames and suspension components, where aluminum alloys have not conventionally been used, the result of demands for further weight reduction. Active research and development programs, including vacuum die casting, other casting technologies and new alloy development, have been implemented to support these new applications (1, 2, 3).

This increase in the volume of aluminum die cast components has resulted in the demand for a long and stable die mold service life. Factors such as heat check, soldering and corrosion-erosion have been conventionally identified as causes of die damage. Heat check countermeasures include a more homogeneous material structure, improved high-temperature strength and die surface cooling. For soldering, it has been reported that the problem occurs when the die is opened at high temperatures to remove the part. To cope with the issue, known measures are application of modified surface treatments, as well as improvements to cooling processes, i.e., optimized water cooling hole layout, cooling methods and surface cooling enhancements (4, 5). Furthermore, to prevent die corrosion-erosion, since the damage is thought to be caused by hot molten materials contacting the die at high speeds, which leads to local over-heating, enhanced cooling and surface treatment are two typical methods to tackle the issue, as in the cases of local erosion and soldering. The use of a high thermal conductivity material is considered to be an effective solution to all these technical issues, due to the fact that it lowers the die surface temperature (6, 7).

Considering actual production operations, efforts to reduce product costs are always required. To this end, measures for cost reduction have been implemented focusing on improving casting yield and production efficiency. As shown in Fig. 1, to reduce cost by improving yield, casting quality improvements such as reductions in internal defects are necessary, while for production efficiency improvements, higher cycle time is thought to be more effective. Whichever direction is taken, the method of die cooling will remain a serious issue. Conventional die cooling has evolved through improvements to water cooling hole layout and external cooling. However, internal and external cooling are limited by technical aspects and for this .issue, attention was focused on temperature reduction using a high thermal conductivity material. Copper and tungsten alloys are both high thermal conductivity materials and there have been instances where these materials have been used locally, but since the benefits are insufficient compared with the material cost, they have not been widely applied.

In this research, a new ferrous material offering high thermal conductivity, regarded as effective in preventing heat check and soldering, was developed and the results were verified in an actual die application. The developed steel retains material properties equivalent to those of the conventional 5% chromium hot work tool steel, AISI-H13 (H13), while ensuring thermal conductivity about 50% greater than H13. In the application of the developed steel to a die, the thermal stress generated on the die surface and surface temperature changes were predicted using FEM analysis, and the feasibility of application to an actual die was shown. Moreover, to confirm the validity of the analysis results, the material was used to produce the engine block water jacket core of a high-pressure die casting machine and the cylinder head upper die of a low-pressure die casting machine, and die temperature changes were verified, demonstrating the effectiveness of the high thermal conductivity material.

Material Development and Predicted Effects

Concept Behind Material Development and Properties

The material was developed with the aim of lowering the die surface temperature and decreasing thermal stress by reducing the temperature gradient within the die by means of a thermal conductivity 50% higher than that of H13, while ensuring the hardness of the conventional hot work tool steel (35 HRC or greater). Material development proceeded taking into consideration the relationship reported by Miettinen et al. (8), given in Eq. 1, regarding the effect of each alloy element on thermal conductivity.

$$\begin{aligned}\lambda(\mathrm{W/m/K,\ RT}) = {}& 80.5 - 45.03\cdot\mathrm{C} + 21.85\cdot\mathrm{C}^2 - 31.69\cdot\mathrm{Si} + 11.5\cdot\mathrm{Si}^2 \\ & - 15.32\cdot\mathrm{Mn} + 0.959\cdot\mathrm{Mn}^2 - 8.091\cdot\mathrm{Cr} + 0.452\cdot\mathrm{Cr}^2 \\ & - 4.674\cdot\mathrm{Mo} + 0.204\cdot\mathrm{Mo}^2 - 3.78\cdot\mathrm{Ni} + 0.084\cdot\mathrm{Ni}^2 \quad (1)\end{aligned}$$

A minimum of 0.2wt% C was set to ensure a composition with a maximum hardness of 40 HRC. Moreover, the alloy was designed while focusing on quenching control to guarantee the material strength. The alloy design targets and composition are shown in Table 1.

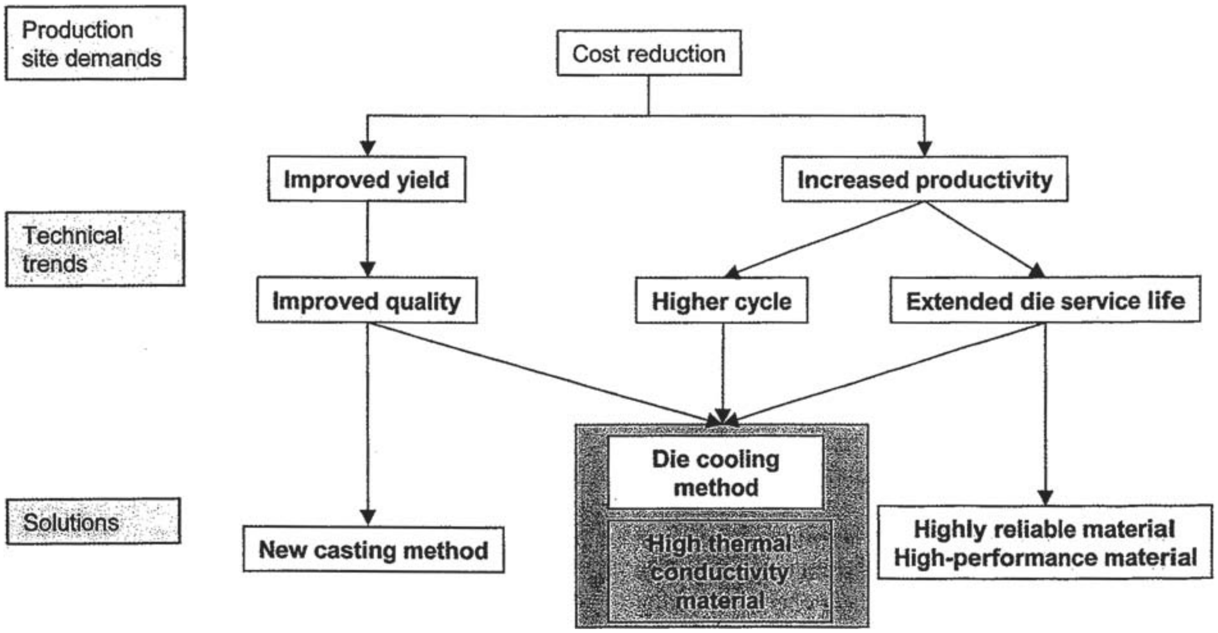

Figure 1. Cost reduction measures focused on improving casting yield and production efficiency.

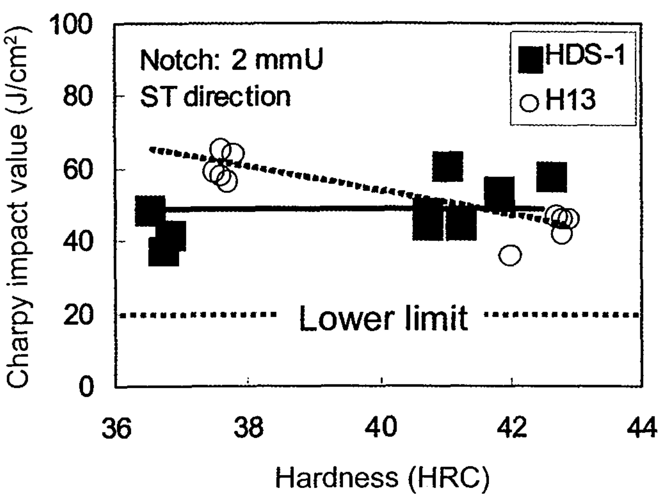

Figure 2. Charpy impact values vs. hardness of the developed and conventional steels are shown.

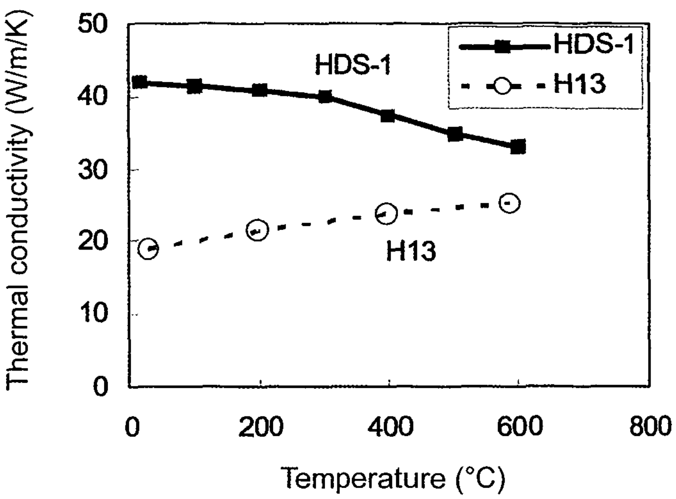

Figure 3. Thermal conductivity vs. temperature of the developed and conventional steels.

Table 1. Alloy Design Concept and Principal Chemistry

	Thermal Conductivity	Hardnability	Maximum Hardness
Target of Property	H13×1.3	≧ 5℃/min	≧ 40HRC
Alloy Design	Low Alloy	Optimization of Mn,Cr	More than 0.2mass%C
Composition of HDS-1	0.22C-LowSi-1.5Mn-1.9Cr-1Mo+add		

Table 2. Representative Properties of Developed and Conventional Steels

Steel	HDS-1	H13
Hardness (RT)	37 HRC	42 HRC
Young's modulus (RT)	210 GPa	208 GPa
Thermal conductivity (500 ℃)	35 W/m/K	20 W/m/K
Thermal expansion ratio (RT-500 ℃)	1.73 × 10^{-5}/K	1.64 × 10^{-5}/K
Fracture toughness (RT)	60 MPa·m$^{1/2}$	72 MPa·m$^{1/2}$
Impact value / 2 mmU (RT)	45 J/cm^2	47 J/cm^2

The main material properties of HDS-1 are shown in Fig. 2 and 3 and in Table 2. Figure 2 shows the results for the hardness and Charpy impact values. A hardness of 40 HRC or greater for the developed steel ensures an impact value of 20 J/cm^2, the value needed to prevent damage in the die's initial use stage [9]. Figure 3 shows the relationship between the temperature and thermal conductivity. The thermal conductivity of HDS-1 is about double that of H13 at room temperatures and about 1.3 times as great at 600°C, ensuring the target is met. Table 2 summarizes the results of investigating the representative properties of HDS-1 and H13. The developed steel has a higher thermal conductivity while maintaining all these representative properties at a level equivalent to H13.

Effect of Increased Thermal Conductivity Confirmed by FEM Analysis

FEM analysis was used to confirm the effects of high thermal conductivity on changes in die surface temperature and surface thermal stress to see what kinds of effects could be expected when applying the developed high thermal conductivity material to die casting dies. Table 3 shows the boundary conditions used in analysis, with calculations performed with the aluminum alloy hypothesized to be in contact with the die surface of the cylindrical model in Fig. 4. The principal stress (thermal stress) at the monitoring point on the die surface is shown in Fig. 4 for H13, which is widely used in die casting die materials, and for the developed HDS-1. Assuming the same die configuration, this thermal stress for HDS-1 is about 60% that for H13, and it was found that there is a tendency with both materials for the thermal stress generated on the surface to increase with larger die shapes. Figure 5 shows the temperature changes in the developed steel against those in H13 for the same configuration (diameter = 90 mm). As seen in this figure, the maximum surface temperature was approximately 30°C lower, with the surface temperature dropping quickly after reaching the maximum temperature. This lower surface temperature leads to a reduced reaction between the die material and the molten aluminum at the die surface, which suggests that molten metal soldering onto the surface may also be reduced (10).

Results of Application of the Developed Steel and Analysis

Results of Application to the Water Jacket Core of the Cylinder Block Die

Service life was evaluated using HDS-1 for the water jacket core of the cylinder block die, which has a comparatively short service life and for which local cooling is problematic. The results are shown in Table 4. The use conditions for both HDS-1 and H13 were identical, with the surface treatment for both being nitriding. Die service life was improved by about 50% over the conventional material.

Table 3. Boundary Conditions Adopted for FEM Analysis

	Pouring	Air cooling	Spray cooling	Air cooling
Time (sec)	5	10	5	10
Temperature (℃)	640→400	23	23	23
Heat transfer coeff. (W/m/K)	30,000	20	2,000	20

Table 4. Application to Water Jacket Core (HDS-1: n-1)

Steel	**HDS-1**	H13
Relative service life	**150%**	100%
Surface treatments	Nitriding	Nitriding
Disposal factor	Crack at upper portion	Crack at upper portion

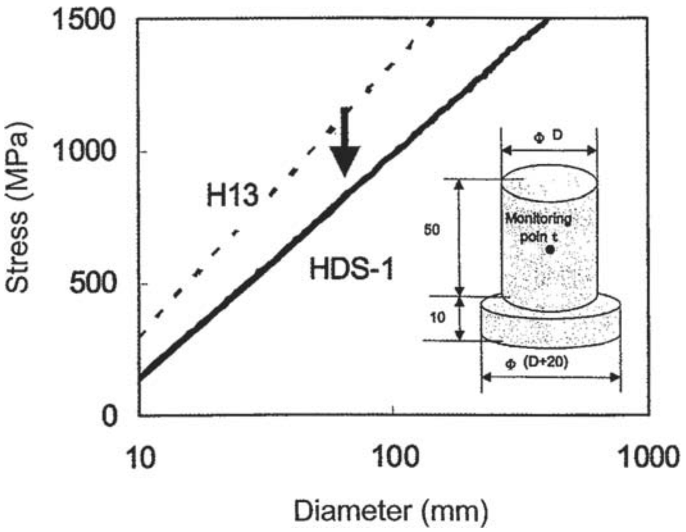

Figure 4. Mold dimension vs. calculated stress values are depicted above.

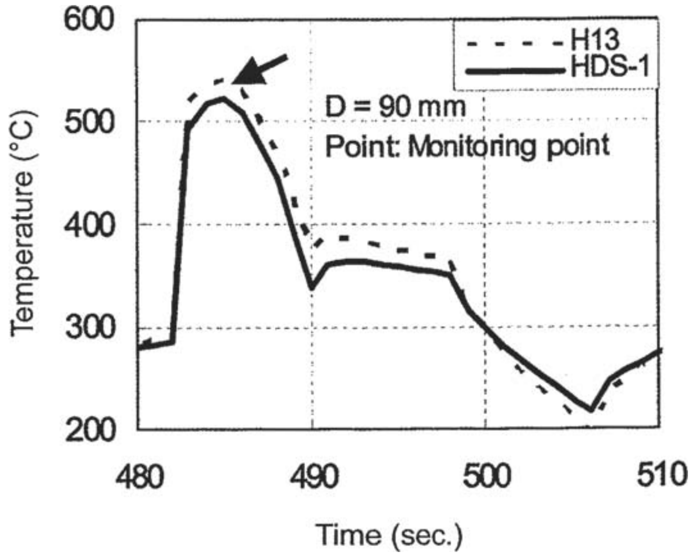

Figure 5. Temperature changes on the mold surface over time.

Figure 6 shows images of the water jacket core surface temperature taken with a thermo viewer. The top image shows the component immediately after removal following casting, while the bottom shows the casting immediately after die cooling spray completion. Lower temperatures are shown in blue, with the temperature increasing in the order of green, yellow, red and white. The areas where the HDS-1 die surface temperature was high following casting removal and cooling spray were smaller than in H13. The water jacket core area immediately after casting removal was white at 300°C or higher, with the HDS-1 area approximately half that of H13.

The decrease in the die surface temperature led to investigation of the solidified structure near the surface area of contact between the aluminum casting and the HDS-1 die, the results of which are compared with the H13 die in Fig. 7. The solidified structure seen in the uppermost layer was finer for HDS-1, and thus, casting strength was assumed to have improved. Because of the effect of the increased strength resulting from this finer structure, the pressure leakage ratio for this cylinder block was about 10% lower than with H13, as shown in Fig. 8, and was determined to contribute to a reduced casting defect ratio. From the above, it can be concluded that, when high thermal conductivity material is applied to the water jacket core, the thickness of the solidified chill zone making up the surface increases with decreases in die surface temperature, leading to improved casting quality (11).

Application to Low-Pressure Dies

Because a lower surface temperature and finer cast structure were confirmed when the high thermal conductivity material was used for the water jacket core, it was applied to the upper die cavity of a large cylinder head die used in a low-pressure casting machine, with the aim of producing a finer cast structure, directional solidification from the upper die and improved productivity due to lower die temperatures. Figure 9 shows the area of the cylinder head upper die with HDS-1 applied. The developed material was used for the upper die (upper cavity), the frame fixing the upper cavity, the cooling block to cool the upper cavity, and the journal pins on the right and left sides.

The results of observation with a thermo viewer of the changes over time in die surface temperature after unclamping are shown in Fig. 10. At its maximum, the HDS-1 surface temperature immediately after unclamping was about 50 °C lower than that of H13. Even after allowing some time to pass following unclamping, the HDS-1 die surface temperature was lower than that of H13 over the entire surface of the upper die cavity. Next, a thermocouple was fixed 10 mm below the die surface and changes in die temperature were measured. Figure 11 shows the measured die temperature changes. Both the maximum and minimum temperatures reached were lower for the HDS-1 die compared with that of the H13 die, with the temperature range during one cycle at about 60°C for HDS-1 and about 50°C for H13.

The areas where the microstructures of the casting produced with HDS-1 and H-13 were investigated are shown in Fig. 12. The areas in yellow are those areas where the HDS-1 and the H13 dies are in contact with the castings. To compare the microstructures, position No. 14 was chosen, where the differences are comparatively clear in the casting cross section. Figure 13 shows the microstructure at position No. 14. Compared with the H13 die, it was found that the product microstructure was finer in the case of the HDS-1 die.

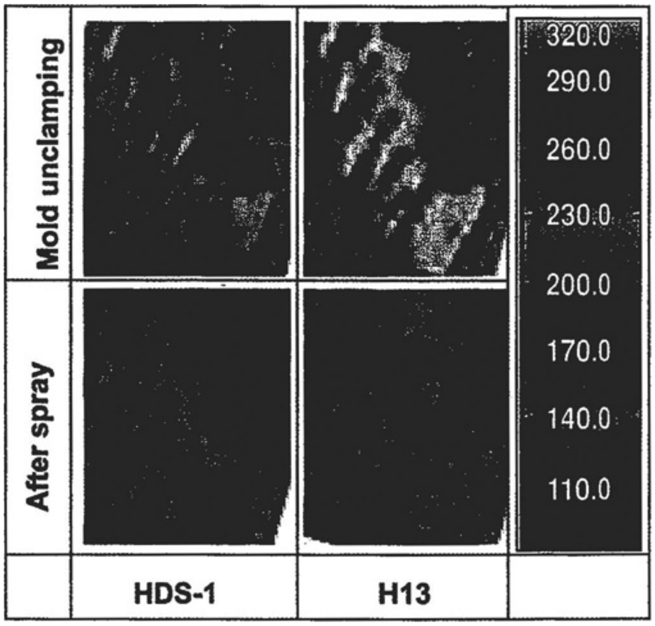

Figure 6. Temperature distribution on the water jacket core surface is shown.

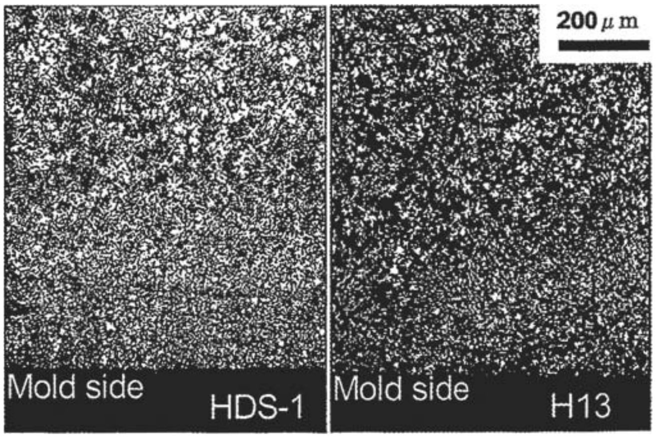

Figure 7. The microstructure of castings that were in contact with the core.

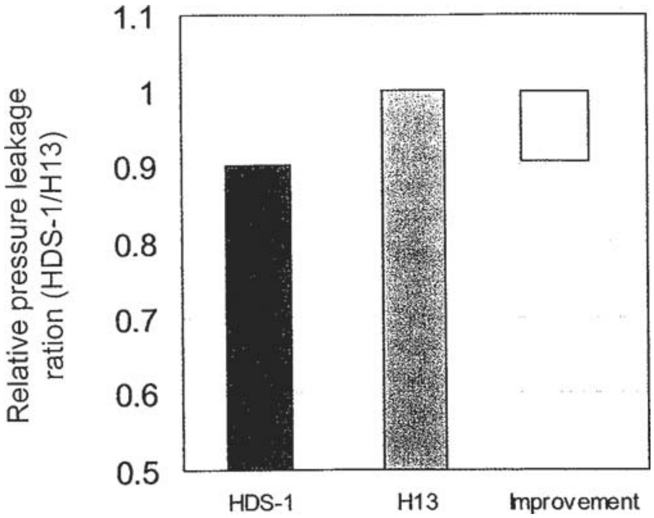

Figure 8. Relative pressure leakage ratio for the developed steels are shown.

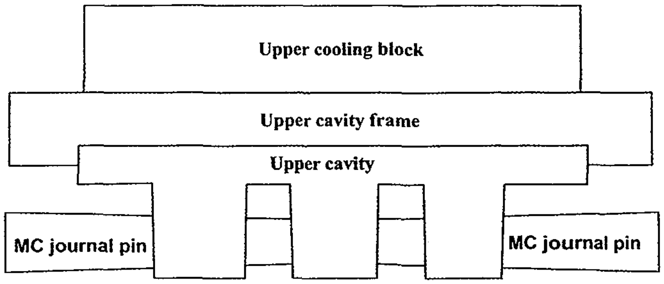

Figure 9. Layout of cylinder head die HDS-1 application areas.

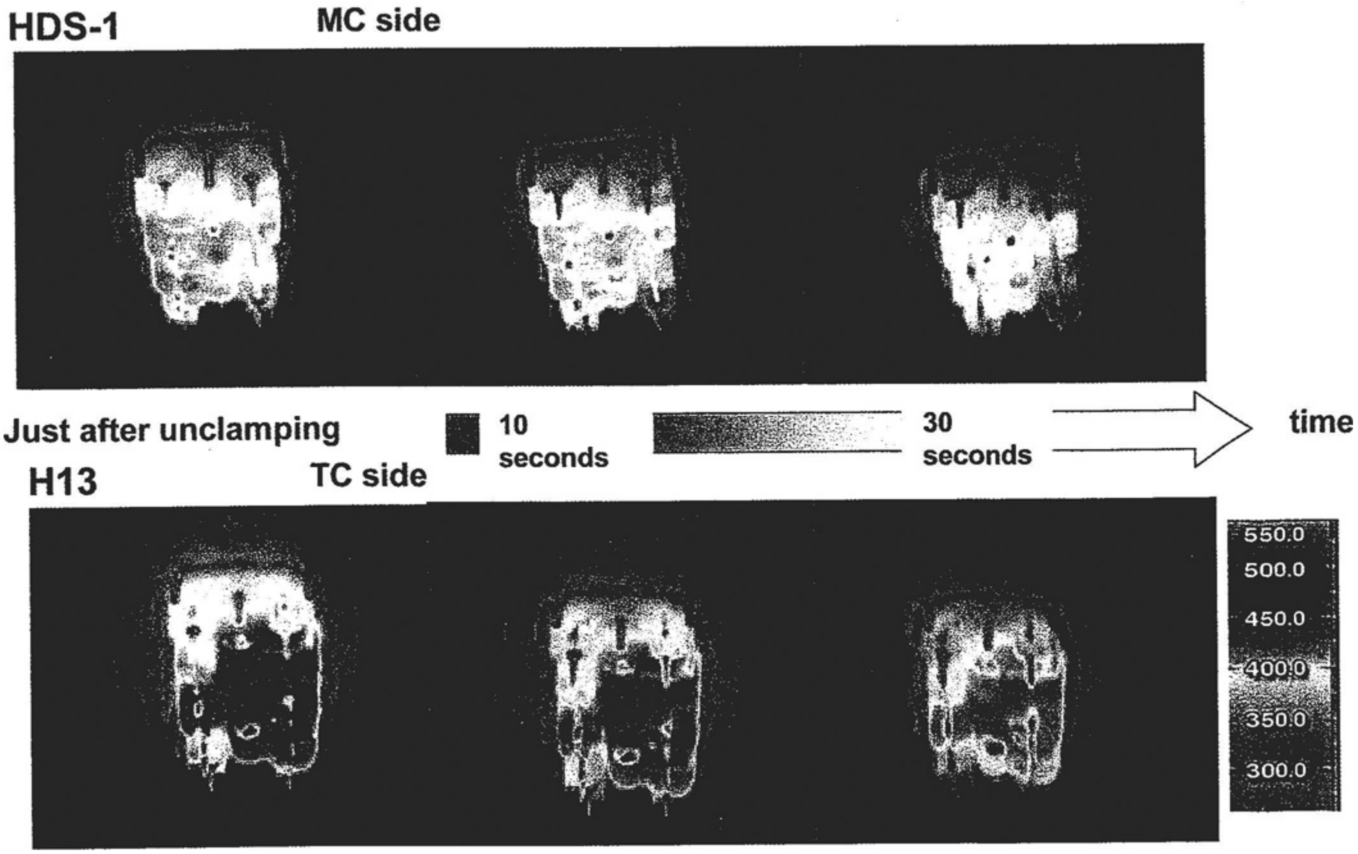

Figure 10. Temperature distribution changes in the cavity of the mold surface after unclamping.

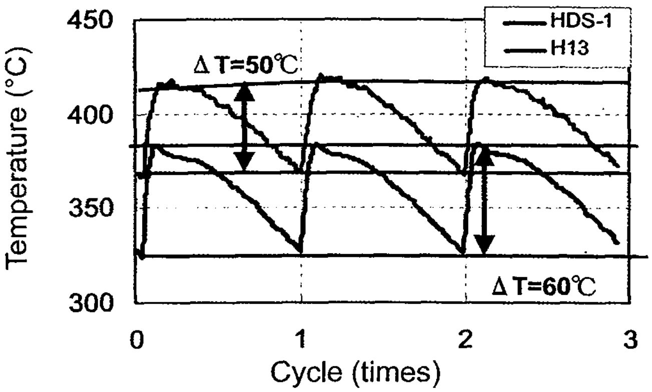

Figure 11. Changes in the internal die temperature are depicted above.

The relationship between the cooling rate for the aluminum alloy and the secondary dendrite arm spacing (SDAS) as reported by Spear et al. (12) and shown in Fig. 14 was linear and nearly the same, regardless of the type of steel. The results of multiple regression for the relationship between the SDAS and the cooling rate in Fig. 14 are shown in Eq. 2.

$$R = \exp((3.8945 - \mathrm{Ln}(SII))/0.3498)$$

SII: Secondary dendrite arm spacing (μm) (2)

For SDAS measurement, after observation of the solidified structure at each site, the spacing between ten dendrite arms was measured and the average cooling rates for these areas were found using Eq. (2) and SDAS avg., the average spacing for these areas. Using this average SDAS value, the predicted cooling rate from Eq. 2 for the casting produced using the HDS-1 die was 7.5°C/sec., whereas that produced with the conventional H13 die was predicted to be 2.2°C/sec., as shown in Fig. 13, and thus, the predicted cooling rate was approximately three times faster for HDS-1. A comparison of the average cooling rates for the entire casting and for the upper region is shown in Table 5. As a reference for comparison, the average cooling rate for the entire H13 cross section was set as 1. The average cooling rate for the entire casting produced with HDS-1 was about 1.5 times faster than with H13. Comparing the average cooling rate of the upper region of the casting (boundary marked with the red line), the H13 casting was confirmed to be about 1.2 times faster, and 1.8 times with HDS-1, which shows the directional solidification from the upper cavity side.

Thermocouple measurements of temperature changes during solidification in the center area of the casting and the area near the gate are shown in Fig. 15. Solidification was defined to be complete when temperature changes in the aluminum settled around 560°C and the time required from start to completion of solidification was obtained. The cycle time required for solidification in the center area of the casting produced with HDS-1 was about 7% shorter than in the casting produced with H13. Meanwhile, no significant difference was seen between the two types of steel in the solidification time for the gate area, which is at a distance from the upper die. From the above results, reductions in both the die temperature and the die surface temperature were confirmed when HDS-1 was applied as the die material for a low-pressure casting machine. Due to this lower die temperature, the product cooling rate improved, leading to smaller SDAS.

CONCLUSION

Conventionally, application to aluminum die casting of the high thermal conductivity materials copper and tungsten has been limited because of strength and cost. Although the thermal conductivity of the HDS-1 material featured in this research is not as high as that of copper or tungsten, this die material was developed with a focus on practicality.

In this research, HDS-1 was developed, a ferrous material with high thermal conductivity fit for application to die casting dies. The developed material was used to produce a water jacket core, achieving a service life approximately 50% longer than that with the conventional material. The use of a high thermal conductivity material was found to lower the die surface temperature and the solidified chill zone making up the cast surface was found to be thicker, leading to improved quality and a 10% improvement in yield. Moreover, applying the developed high thermal conductivity steel to a low-pressure die casting machine resulted in a lower die surface temperature than with a conventional die, and the internal die temperature was also confirmed to be about 30 to 40°C lower. Because of this reduced die temperature, the SDAS structure was finer, and it is hypothesized that a directional solidification starting from the upper die cavity with the developed steel towards the lower die cavity was realized. Additionally, since the cooling rate was faster than for the conventional steel, a shorter casting cycle can also be expected.

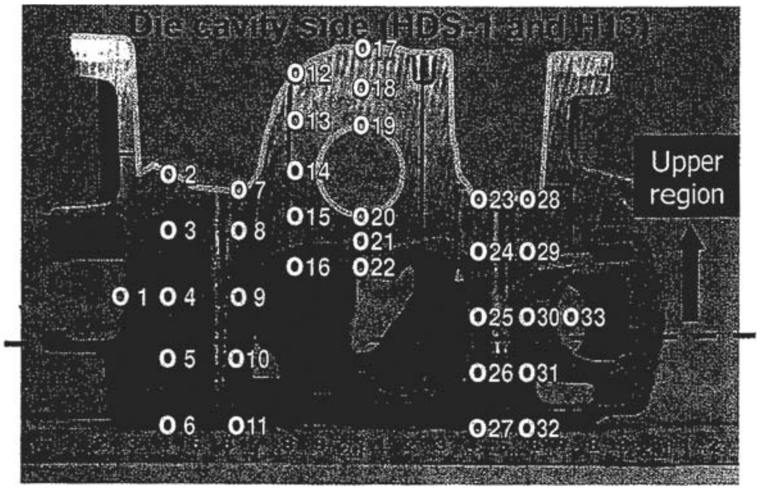

Figure 12. The actual position of microstructure observation areas are shown on the casting.

Finally, the HDS-1 die was applied to a large insert die, a small insert die, and core pins among other components, and the service lives of these tools and casting quality were evaluated. The result of these tests was improved tool service life and product quality when HDS-1 was used in the small insert die and the core pins. In the future, appropriate areas of application for the developed steel and conditions for application should be clarified.

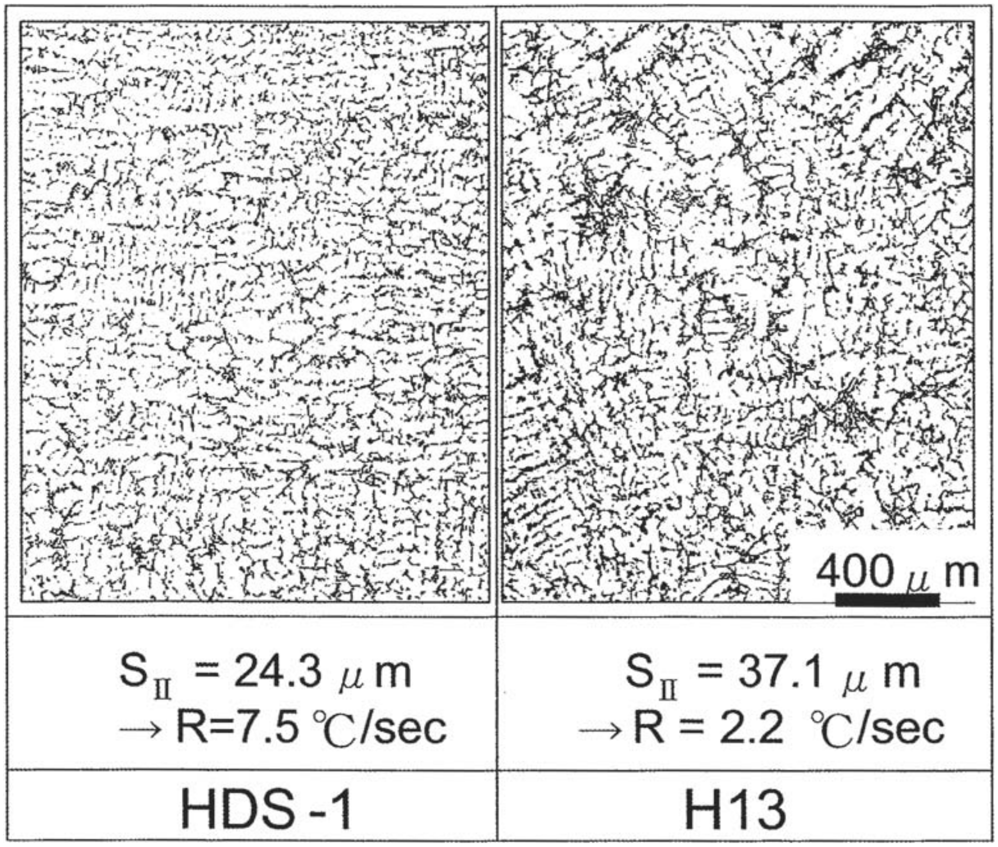

Figure 13. Micrographs of the solidified structure of HDS-1 and H13.

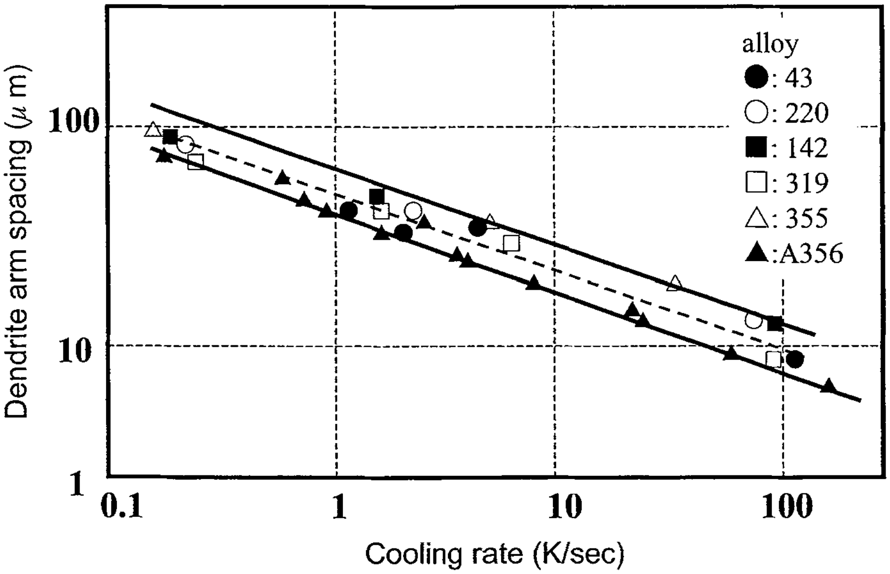

Figure 14. The relationship between cooling rate and dendrite arm spacing is shown for the various alloys. (Data from Spear et. al: Modern Castings 43 (1963): 209).

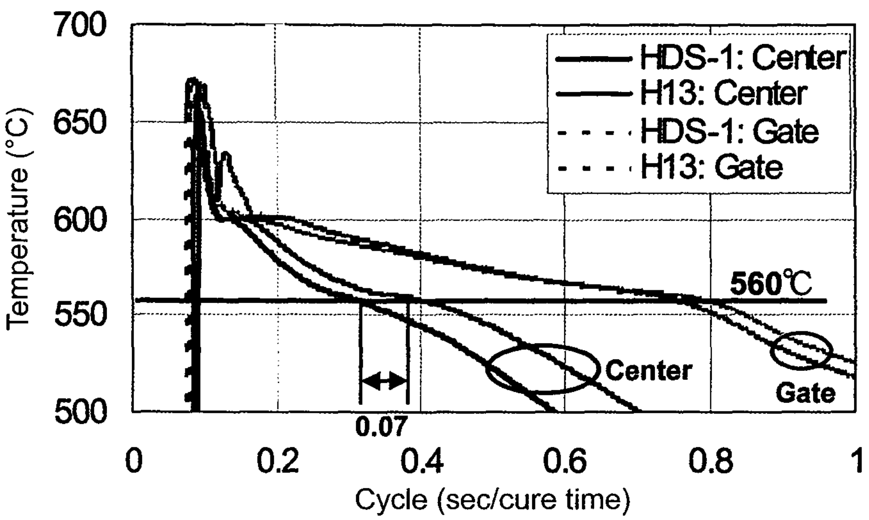

Figure 15. Product solidification data as it relates to location.

Table 5. Relative Cooling Rates of Castings

Position	HDS-1	H13
Relative cooling rate of average of all region	1.48	1.00
Relative cooling rate of average of upper region	1.81	1.16

Author Contacts

Masahiko Ayabe, Teruhiko Nagaoka, Honda Motor Co., Ltd., Suzuka, Mie, Japan
Kiyoshi Shibata, Hiroshi Nozute, Honda Motor Co., Ltd., Ozu-machi Kikuchi-gun, Kumamoto, Japan
Hiroaki Koyama, Honda Engineering Co., Ltd., Haga-gun, Tochigi, Japan
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