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Abstract

The goal of this work is to study the influence of process parameters upon DAS of cast aluminium cylinder heads. In the first step, in order to evaluate the effect of the chemical composition of the alloy, having a fixed casting geometry, we measured the DAS value upon:

- samples taken from specific simple-shaped castings;
- FIAT JTD cylinder head, that were chosen as reference castings

poured with three different alloys that are commonly used for cylinder head production at Teksid Aluminum. The experimental results showed that increasing the content of alloying elements like silicon or copper brings to a reduction of DAS values.
In a second step, we studied the influence of process parameters which affect the solidification rate of real castings, like liquid metal temperature at pouring, mold temperature, and geometric configuration of the casting in the area of combustion chambers; we found that lower DAS values are obtained more easily by lowering the pouring temperature rather than mold temperature.
Finally, after studying DAS values of cylinder head casting having different geometries in the combustion chamber area, we found that DAS values in the combustion chamber area are lower when the casting solidification shrinkage is fed through the bolt bosses or the camshaft bearings, rather than through the spark plug towers or the fuel injector bosses.
All the samples were taken from the production of Teksid Aluminum plants which cast aluminium alloy cylinder heads in gravity semi-permanent mold technology.
The data obtained from this study will be used to improve process control, and to help the selection of the alloy and the design of the casting and of the gating/feeding system for future products.

Riassunto

Obiettivo di questo lavoro è lo studio dei parametri di processo che hanno influenza sul DAS di teste cilindri prodotte in lega di alluminio.
In una prima fase, al fine di valutare a parità di geometria l'influenza della composizione chimica della lega, la misura del DAS è stata rilevata su:

- campioni prelevati da una provetta colata a parte di geometria molto semplice
- testa cilindri FIAT JTD di riferimento colate con tre differenti leghe di impiego corrente per la produzione di teste cilindri.

I risultati sperimentali hanno messo in evidenza che l'aumento in percentuale di elementi leganti quali silicio e rame, determina una riduzione dei valori di DAS.
In una fase successiva sono stati studiati i fattori di processo che influenzano la velocità di solidificazione dei getti reali, quali la temperatura di colata, la temperatura della conchiglia e la configurazione geometrica dell'area delle camere di scoppio, evidenziando in particolare come valori di DAS piccoli siano favoriti maggiormente dall'abbassamento della temperatura del metallo alla colata piuttosto che dalla diminuzione della temperatura della conchiglia.
Infine investigazioni su teste cilindri con configurazioni geometriche diverse in zona camera scoppio hanno mostrato che il DAS misurato sulle camere a scoppio di teste cilindri alimentate su colonnine/supporti albero a camme risulta minore rispetto a quello rilevato teste cilindri alimentate su sedi candela o sedi iniettori.
Tutti i campioni esaminati sono stati prelevati dalla normale produzione degli Stabilimenti Teksid Aluminum, in cui le teste cilindri sono prodotte mediante colata a gravità in conchiglia.
I dati ottenuti da questo lavoro saranno utili per migliorare il controllo di processo della normale produzione di teste cilindri, per la scelta delle leghe e per la progettazione dei getti e dei sistemi di colata.

INTRODUCTION

The solidification of cast aluminium alloys starts with separation of a primary alpha phase from the liquid. After nucleation, when the temperature lowers, the primary phase grows as solid crystals having dendritic shape. When the eutectic temperature has been reached, the solidification proceeds at constant temperature with the formation of the eutectic solid phase in the space left between dendritic arms.
On the polished samples the two phases can be easily distinguished, and the secondary arms of the dendrites cut on the sample plane clearly appear (fig. 1, white areas).
Dendrite arm spacing (DAS), which is defined as the distance between the protruding adjacent secondary arms of a dendrite, has been used in recent years to describe the metallurgical structure of cast materials. Castings having a finer microstructure show better tensile and fatigue properties and, particularly for cast aluminium alloys, this improvement is related to a lower DAS value.

In fact, the smaller the DAS value, the smaller the size of defects occurring during eutectic solidification, like segregation, microshrinkage and gas porosity, which are detrimental to tensile properties.
The size of the dendrites is affected not only by the chemical composition of the alloy, but also by the casting to mold heat transfer rate during solidification. Because of the evident importance of DAS, more and more automotive companies have defined so far a DAS limit in their engineering specifications for aluminium castings.
A lot of papers has been published in the last 50 years about the factors that influence DAS and the relationship between DAS and mechanical properties of aluminium alloy castings[1-6]. Almost all the above-mentioned researches were based on testing plates separately poured in sand mold, in which the solidification rates needed to achieve various DAS were controlled by varying the chill thickness and its location, or sample dimension.
On industrial casting production it is more difficult to control solidification rate and therefore DAS value for a number of reasons:

- the complexity of the shape of engine parts, having many cavities in close proximity
- the need for directional solidification in order to obtain castings free from macro-defects and with satisfactory quality in the whole casting volume,
- efficient heat removal is possible only close to the mold walls,
- the gating/risering system is affected by the part geometry.

Therefore, after a first test step on simple-shaped castings, this study turned to DAS values of real complex-shaped castings like cylinder heads from Teksid Aluminum mass production, and particularly to the effect of the alloy composition (pouring the same casting shape with several alloys commonly used in our plants), and then to the effect (keeping constant the alloy composition) of process parameters like liquid metal temperature or mold wall temperature close to cooling system.

TEST PROCEDURES

DAS measurement

The 2nd arm method, as shown in Fig. 2, was used to calculate the DAS thet equals the total distance divided by the numbers of arm spacings and multiplied by a magnification factor. For each specimen 2 photos were taken and the mean DAS value was calculated from 10 measurements.
The specimens for optical microscope were prepared by the normal metallographic technique of mounting, polishing and etching.

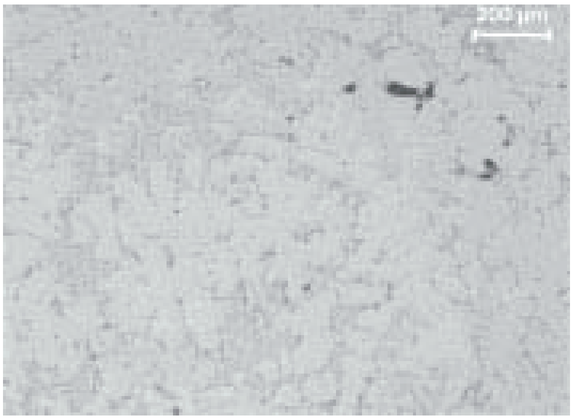

Fig. 1: AS7U3 alloy after solidificaiona in sand, 50x. The picture shows the primary solidification areas (white) surrounded by eutectic areas.

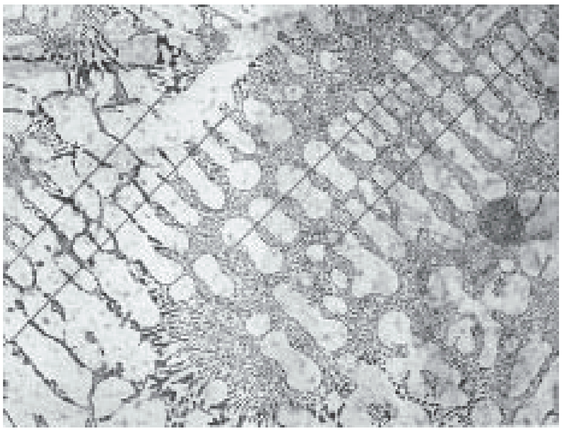

Fig. 2: Method of measurement of DAS: ratio of segment length to number of arms

Sampling areas

The DAS value of cylinder heads has been evaluated on specimens cut from the combustion chamber area as shown in Fig. 3, as it is required by most of the customers' specifications. In fact these areas are the most thermally and mechanically stressed ones, therefore here the evaluation of microstructure is required. The depth from casting surface where the DAS was measured was 1 mm for cylinder heads after machining.

Alloy used

To evaluate the effect on DAS of the alloying elements, three aluminium alloys currently used in the Carmagnola Plant for production of various

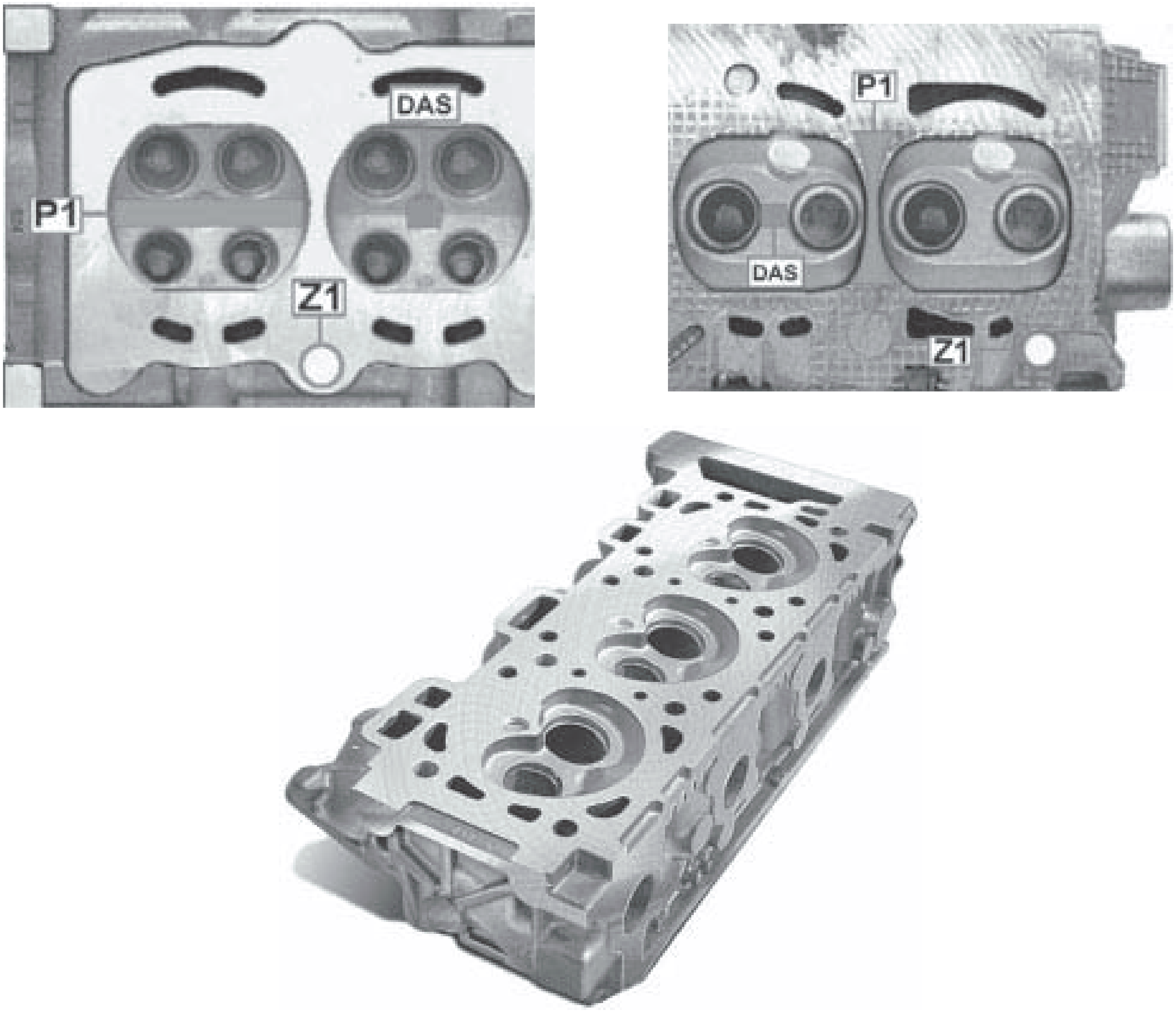

Fig. 3: Parts of a)Fiat Fire cylinder heads 8V b) Fiat Fire cylinder heads /16V and c)Ford V6 cylinder head (Alloy AS7U3).

gasoline and diesel cylinder heads are chosen for this study. They are GAS7GT, GAS9C1 and AS7U3; the first is a hypoeutectic Al-Si type alloy and the last two are hypoeutectic Al-Si-Cu alloy. (Table 1).

TABLE 1. ALUMINIUM ALLOYS IN USE FOR CYLINDER HEAD CASTING IN TEKSID CARMAGNOLA PLANT

	Alloy	Standard	Customer	Chemical composition					
				Si	Cu	Mg	Ti	Fe	Mn
Diesel engines	GAS7GT (A356)	AFS	Hyundai	6.5 – 7.5	Max. 0.2	0.25 – 0.45	0.10– 0.20	Max. 0.2	Max. 0.1
	GAS9C1 (354)	FIAT	FIAT IVECO	9.0 – 10.0	0.8 – 1.3	0.25 – 0.5	Max. 0.1	Max. 0.3	Max. 0.1
Gasoline engines	AS7U3 (319)	FIAT	FIAT FORD	6.5 – 8.0	2.8 – 3.5	0.25 – 0.5	Max. 0.25	Max. 0.8	Max. 0.5

Cylinder head castings

To evaluate the effect of chemical compositions on DAS, three different alloys was used to cast the Fiat JTD 1.9 L 2v cylinder head (Fig.4), at the same pouring temperature with the same mold and production cycle.
For a given alloy, the study of the factors affecting DAS was performed on Hyundai cylinder head 2,0 L D.I. 4v Diesel cast in GAS7GT alloy, (Fig. 5), and on Fiat fire 8v, 16v, Torque 16v, Ford explorer V6 cast in AS7U3 alloy (Fig. 3).

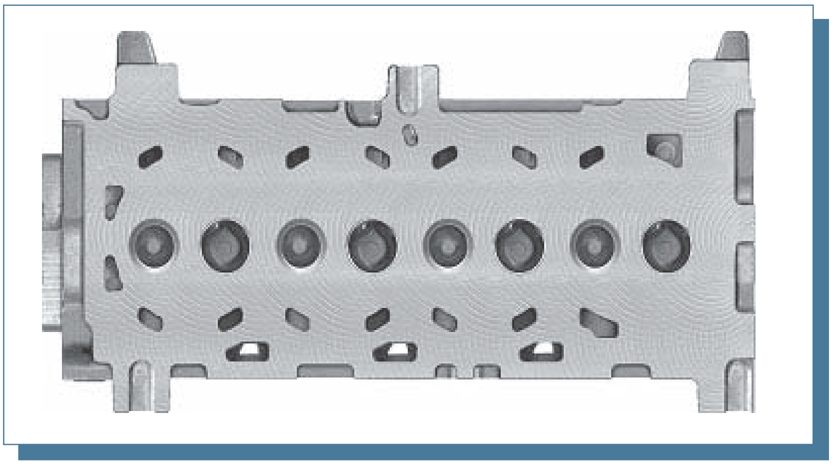

Fig. 4: Fiat JTD cylinder head 1.9l (net weight 12.5 Kg.

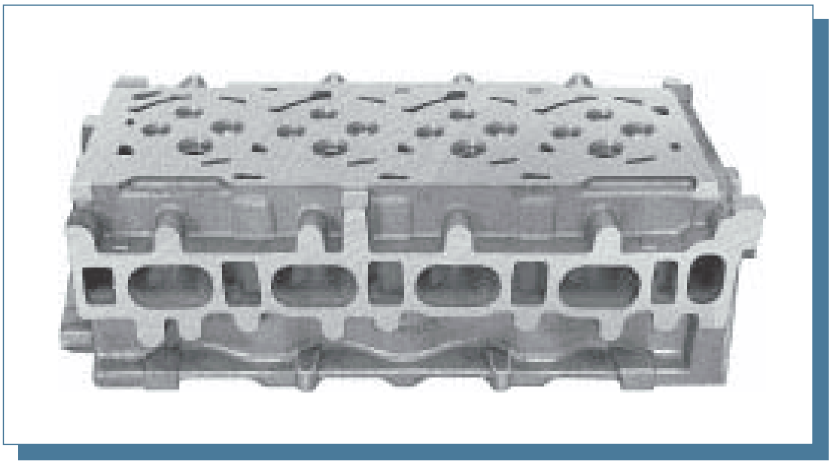

Fig. 5: Hyundai cylinder head 2.0 lL (net weight 14.5Kg).

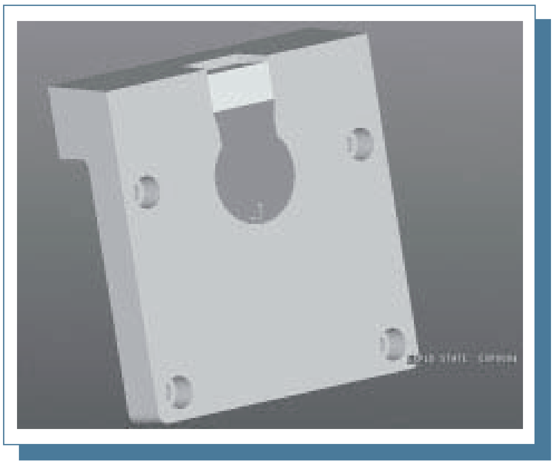

Fig. 6: . Mold for separately poured samples of DAS.

Results and discussion

Effect of chemical composition on DAS: separately poured samples

Samples were separately poured in a metal mold, shown in fig. 6, using the above mentioned alloys. For DAS measurements, specimens were cut from these castings,.
The results are reported in Table 2. The values refer to measurements in the center of the disk-like castings.
Although the same pouring parameters were used for the three alloys, and the casting geometry was very simple and with a very high solidification rate due to the steel walls of the mold, the DAS values were different between the alloys. Particularly, the AS7U3 having the same silicon content as GAS7GT but also 3% copper, shows lower DAS values. The GAS9C1, having higher silicon but an intermediate copper content, shows intermediate DAS values.

Table 2. DAS values for separately poured samples in different alloys

Alloy	T. of furnace (°C)	T. of pouring (°C)	Mean DAS (µm)	DAS max. (µm)	DAS min. (µm)
GAS9C1	730	705	17.1	19.5	15.5
AS7U3	730	705	15.9	18.8	14.0
GAS7GT	720	705	20.2	22.1	16.7

Effect of chemical composition on DAS: Fiat JTD cylinder head

The Fiat JTD cylinder head was cast with various alloys. DAS values of this product using GAS9C1, AS7U3 and GAS7GT , as reported in Table 3.

Different alloys resulted in different DAS for the same cylinder head cast with the same mold using the same production cycle, although the temperatures of furnace and pouring are similar. The order of DAS values for the alloys is GAS7GT>GAS9C1>AS7U3. The same order was confirmed

TABLE 3. DAS VALUES FOR SEPARATELY POURED SAMPLES IN DIFFERENT ALLOYS

Alloy	T. of furnace (°C)	T. of pouring (°C)	Mean DAS (µm)	DAS max. (µm)	DAS min. (µm)
GGAS9C1	730	718	21.5	27	18
AS7U3	732	720	20.7	24	16
GAS7GT	729	718	26.4	36	20.6

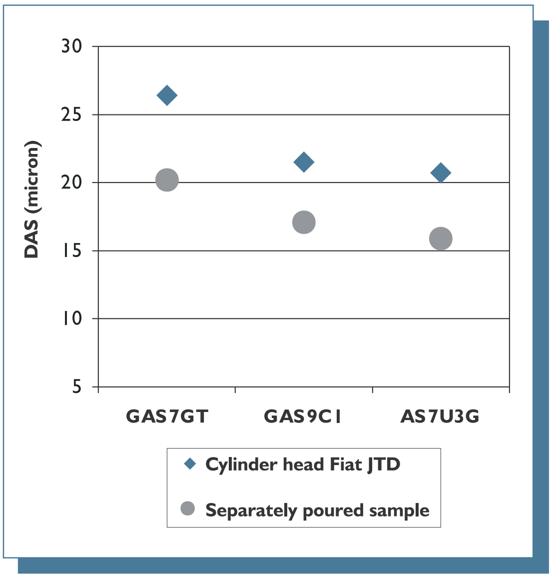

Fig. 7: DAS of different alloys, poured in separately mold and in the same cylinder head.

by the study on the separately poured samples [7]. The results are summarised in Fig. 7 for separately poured specimens and cylinder head.
The results can be explained by the composition versus dendrite cell size curves produced by Spear and coworkers [1] and reported in Fig. 8. The figure clearly shows the influence of four major alloying elements for aluminium alloys upon dendrite. The alloying elements show an appreciable refining effect as the content varied from 0 to 5 per cent by weight. When the alloy content was increased above 5 per cent, the dendrite cell size continued to be refined, but at a much lower rate.
The alloys used at Carmagnola Plant, as shown in Table 1, have a silicon content over 5% (the magnesium content is similar and the zinc content is very low for all alloys). So for two types of Al-Si-Cu alloy such as GAS9C1 and AS7U3, the copper content which varies from about 1 to 4 per cent, plays a more important role than silicon in reducing DAS. In detail (see Fig. 7), alloy GAS9C1 has a DAS smaller than GAS7GT because of the effects of both silicon and copper. But if we compare GAS9C1 with AS7U3, the former shows a larger DAS than the latter although its silicon content is higher. This is because of the effect of copper whose content in AS7U3 alloy was more than 3% while the copper content in GAS9C1 was only about 1%.

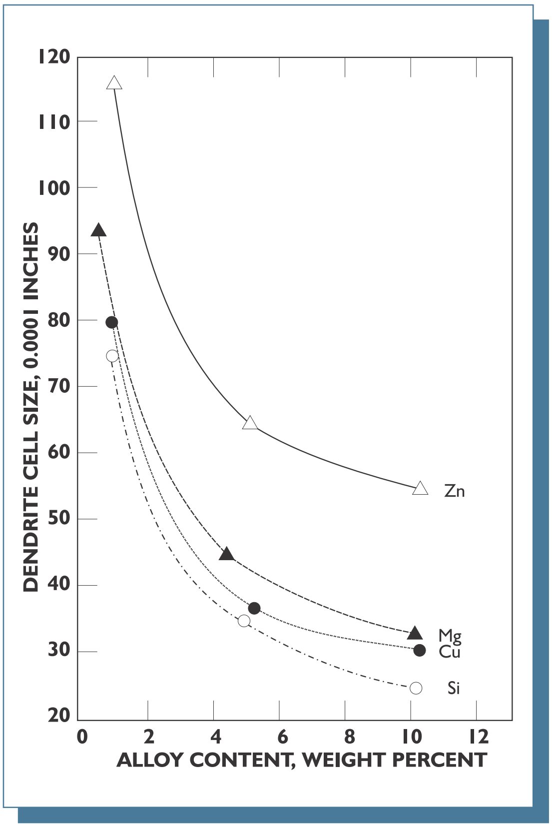

Fig. 8: Relationship between alloy content and dendrite cell size for four alloying elements in aluminium. The cooling rate for all alloys was 0,75 F/sec. By Spear and Gardner, "dendrite cell size"[1].

Effect of process parameters on DAS.

When the alloy composition of a cylinder head has been decided, the solidification rate will be the most
important factor to determine DAS. In normal production of a cylinder head, the factors that can
affect the solidification rate can be summarised as:

- local temperature of the mold, especially in the area of combustion chambers of the cylinder head, which can be controlled by the cooling system in the mold;
- temperature of liquid metal during pouring (pouring temperature);
- geometric configuration of the cylinder head in the combustion chamber area, and of the risers.

Such factors will be hereafter discussed in several cylinder heads of GAS7GT and AS7U3 alloys.

Effect of mold temperature

Hyundai cylinder head 2.0 l (Fig. 5) was for a diesel engine. The specification of the Hyunday imposed the maximum DAS value being 25 mm. Alloy GAS7GT was used to cast this product. As we have discussed above, the mean DAS value of this alloy was higher than other alloys in use at our plants. Many efforts were made to decrease the temperature of the mold, especially in the area of combustion chambers of cylinder head. Fig. 9 shows the influence of mold temperature in the combustion chamber area on the DAS at the same pouring temperature 720°C. It can be seen that DAS value was reduced from

28 mm to about 22 mm as the temperature deceased from 250°C to about 50°C.

Effect of pouring temperature

Tests were also done on reducing pouring temperature, in a range permitted by alloy metallurgy in order to guarantee the casting quality, for studying its influence on DAS. The results are shown in Fig. 10. It was found that to reduce DAS the decrease of pouring temperature is more effective than the decrease of local mold temperature. From comparison of figures 9 and 10, one can see that on reduction of DAS the decrease of pouring temperature by 20°C has the same effect as decreasing 200°C the mold temperature.

Effect of sample location

Another factor is the specimen location. This means the area from where the samples for DAS measurement were taken out. At 5 mm deep from combustion chamber surface of as-cast cylinder head and 1 mm deep for cylinder head after machining. Fig. 11 shows the relationship between test location (distance from combustion chamber surface along spark plug boss) and DAS. Certainly DAS increases with the depth because of the delay in solidification, compared to the surface.

Influence of geometric configuration of cylinder head

Investigations on various cylinder head castings in alloy AS7U3 revealed that the influence of temperatures (either pouring temperature or temperature of the mold in combustion chamber area) on DAS was complex. If Fiat Fire 16V is compared with Ford V6 (Table 4), the pouring temperature for the latter was 20°C higher than for the former; moreover, the temperature of the mold in the DAS sample area for Ford V6 was about 100°C higher than that for Fiat Fire 16V; however the Ford V6 cylinder head had a DAS lower than Fiat Fire 16V. The result underlines the importance of the geometric configuration of cylinder heads. Fig. 12 shows the geometric configurations of these two types of cylinder head. In general, cylinder heads fed through bolt bosses/camshaft bearings possess a smaller DAS than cylinder heads fed through spark plug bosses.

Table 4 gives pouring temperatures and DAS values of four different cylinder heads in AS7U3 alloy.

In fact, the pouring parameters (including pouring temperature, solidification cycle and cooling

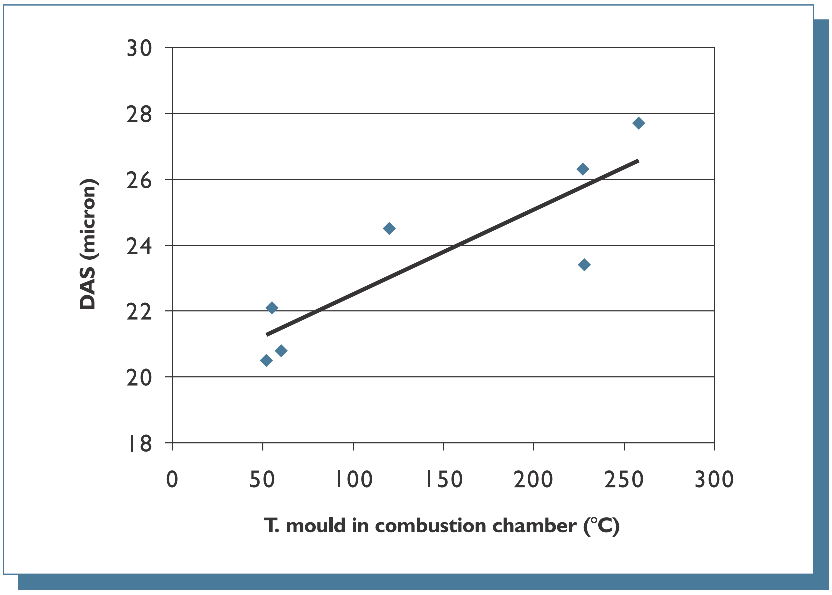

Fig. 9: Relationship between temperature of mold in combustion chamber and DAS for Hyundai cylinder head (Pouring temperature being 720°C).

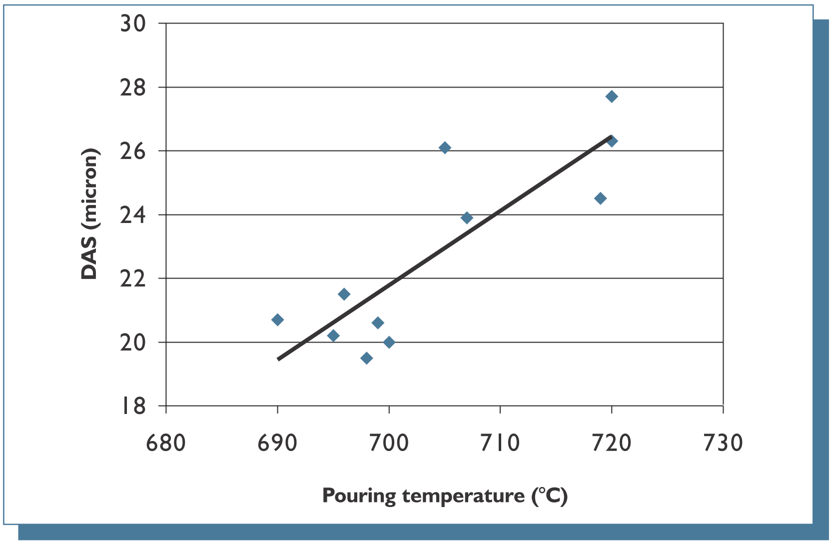

Fig. 10: Relationship between pouring temperature and DAS for Hyundai cylinder head.

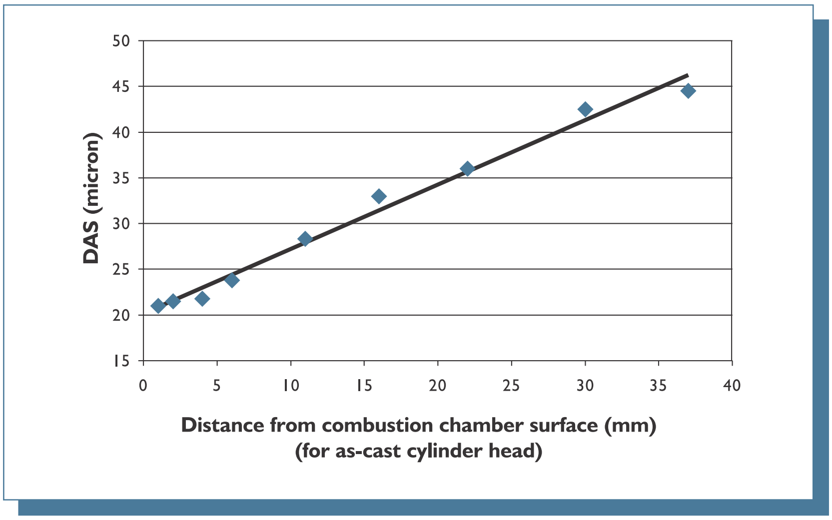

Fig. 11: DAS values of Hyundai cylinder head of different test locations.

Table 4. Pouring temperatures and DAS of different cylinder heads in AS7U3 alloy

Cylinder head	Fiat Fire 8V	Fiat Fire 16V	Fiat Torque 16V	Ford V6
T. pouring (°C)	690	695	705	715
DAS (mm)	20	29	30	27
fed position	bolt bosses/ camshaft	spark plug bosses	spark plug bosses	bolt bosses/ camshaft

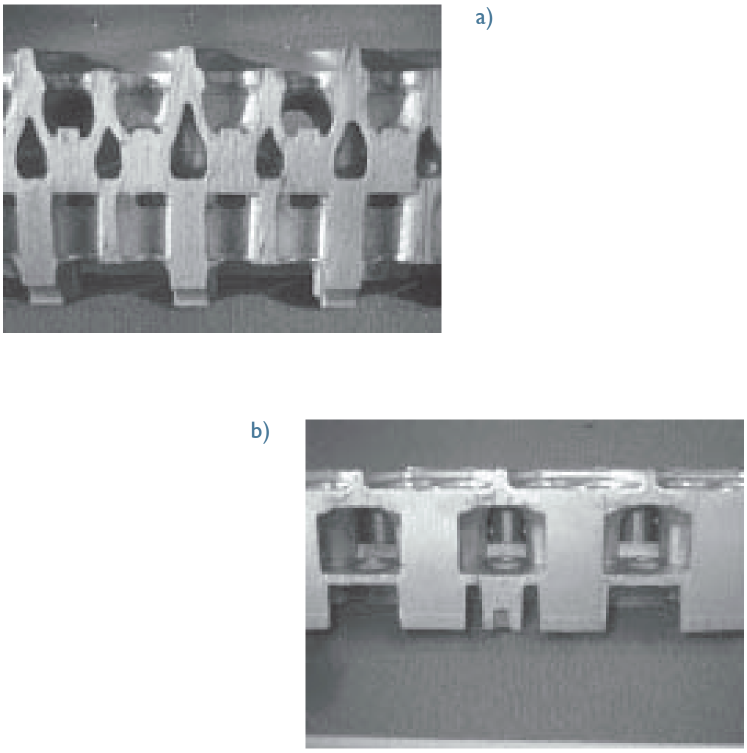

Fig. 12: Geometric configuration of cylinder heads in combustion chamber zone of (a) fed on bolt bosses/camshaft bearings and (b) fed on spark plug bosses.

systems for mold) for Fiat Fire 8V and 16V cylinder heads were very similar, but their DAS values were very different. The pouring temperature for Ford V6 cylinder head was higher than for other castings, but its DAS was smaller than that of Fiat Fire 16V and Fiat Torque 16V, two cylinder heads which are fed through spark plug bosses.
The geometric configuration of cylinder heads resulted in the difference in DAS because it has influence on solidification rate.

CONCLUSIONS

The factors that influence DAS of cylinder heads produced by gravity semi-permanent mold with aluminium alloys were studied. Investigations on either cylinder head or separately poured samples using alloys different in chemical compositions showed that the hypoeutectic Al-Si-Cu alloys such as AS7U3 (319) and GAS9C1 had lower DAS than hypoeutectic Al-Si alloys such as GAS7GT. Both silicon and copper had a remarkable refining effect on DAS as the alloying element content varied from 0 to 5 per cent by weight. In the case of the same pouring temperature, DAS of cylinder heads decreased with decreasing of mold drag temperature. But reducing pouring temperature, in the range permitted by casting metallurgical quality, had a more direct and remarkable effect on decreasing DAS than reducing mold temperature. Excessive pouring temperatures can result in castings with higher DAS and low mechanical properties [8]. Test location and geometric configuration had also influence on DAS. In cylinder head fed through spark plug bosses, DAS increased with increasing of the distance from combustion chamber surface. In general, cylinder heads fed through spark plug bosses showed higher DAS value than cylinder heads fed through bolt bosses/camshaft bearings, because in the former case the metal temperature in the combustion chamber area, where DAS was measured, might be higher than in the latter.

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