論 文

Characterization of Al-15wt.%Si Functional Automotive Component by Partial Squeeze and Vacuum Die Casting Process

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Abstract

본 연구에서는 기존 고압주조법의 해결과제인 고속충진 시 혼입되는 금형 cavity 내부의 유해 gas에 의한 gas porosity를 제어하기 위한 고속 사출 전 진공시스템 설계와 응고과정에서 발생되는 응고수축에 의한 shrinkage를 효과적으로 제어하기 위한 국부가압 스퀴즈의 조합시스템의 설계로 최적의 기계적 성질을 갖는 부품을 제조할 수 있는 공법을 개발하였다. 또한 개발된 신공법으로 자동차용 고내마모성 요구부품인 Reaction Shaft Support에 기존의 주철제를 대체하는 Al-15wt.%Si 과공정합금을 적용하여 시제품을 제조하였으며, 기존의 공법과 비교한 결과, 내부 porosity가 없는 미세하고 균일한 공정 및 초정 Si의 미세조직을 얻을 수 있었고, 기계적 특성평가에서도 매우 우수한 결과를 얻을 수 있었다.

Key words : Hypereutectic Al-Si alloy, Primary Si, Squeeze and Vacuum Die Casting

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1. Introduction

Die casting injects the liquid metal into permanent molds at high speed. This means they have low cycle times and produce accurate castings of good surface quality. Therefore die casting is ideally suited for producing small near net shape artifacts that require good surface without secondary processing.

In the die casting process, the injection stroke can cause a jet of liquid to hit the far end of the mold cavity and then splash backwards. This produces highly turbulent conditions, introduces a lot of air, and results in very poor quality castings. Such castings can be machined only lightly and can not be heat treated because the expansion of the entrapped bubbles causes blisters and distortion. Great improvements in quality can be made in die castings if the injection is done in several stages, each of which is optimized to reduce turbulence. But this requires increased control, and therefore more investment, to produce a good quality product. Inevitably, enhancements designed either to improve product quality or to reduce cycle time will increase cost and so most commercial injection molding processes will compromise between these two elements. Conventional die casting uses pressure to force short freezing range alloys into the die through a relatively narrow gate. It is these very high fluid velocities so developed that are responsible for the inherent high fluidity of the process. However, the turbulent flow created at such high fluid velocities entraps air into the molten metal and despite the applied pressure high levels of porosity are produced as the relatively narrow gate solidifies before the liquid in the cavity solidifies. Controlled injection can reduce air entrapment but porosity is still produced if the molten metal is not fed properly. Several modifications to the pressure die casting have been developed to increase the integrity of pressure die castings. In the ACCURAD process[1], a secondary plunger just after a layer of metal has solidified adjacent to the die cavity wall, is used to feed center-line shrinkage. A larger gate is also designed into the die to reduce turbulence during injection and to

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allow feeding. The secondary plunger operates typically 0.1~1.5 seconds after main plunger stops, depending on the size of casting. However, the lower velocities generated by the larger gate reduce fluidity so that castings can not be as complex or thin walled as in conventional high pressure die casting. An alternative approach is used in pore free die casting[2], which works by replacing the air in the closed die by purging it with oxygen before the molten metal is injected. The oxygen combines with the metal to form fine metallic oxides (typically less than 1 μm), thus reducing porosity. Mechanical properties are improved due to the reduction in porosity and complex castings can be reproduced. However, as the cycle time is increased to allow for the injection of the oxygen, production rates are reduced. Gas free vacuum die casting process[3] reduces the air pressure (below 200mmHg) inside the mold cavity just before the injection of molten metal and drawing the molten metal into the mold cavities through a gate. In this process, the prevention of porosity formation due to vacuum enables good casting qualities both microstructurally and mechanically. But the precise control and maintenance of shut on/off vacuum valve attached on the die limits production rates. The squeeze casting [4] involves solidification of the molten metal under high pressure. The pressure applied by the plunger keeps the entrapped gases in solution, and the contact under high pressure at the die-metal interface promotes rapid heat transfer, resulting in a fine microstructure with good mechanical properties. The application of pressure also overcomes feeding problems that can arise when casting metals with a long freezing range parts can be made to near net shape, with complex shapes and fine surface detail. However, as the cycle time is increased to allow squeezing effect, production rates are reduced and production costs be increased due to squeezing machinery.

Therefore in this study, advanced die casting technique to satisfy high productivity (trouble zero vacuum die casting method) and high quality (controlling porosity and shrinkage) is industrially implemented to produce reaction shaft support by using hyper eutectic Al-Si alloy[5-7].

2. System Design for Squeeze Casting with Vacuum Die Casting

The machinery for making a hybrid of partial squeeze casting and vacuum die casting is schematically shown in Fig. 1.

As shown in Fig. 1, the chill vent type vacuum system was adopted in this study. The spontaneous shutting off effect due to early solidification of leading molten metal at chill vent zone no longer needs the installation of a shut off valve which has been the main cause of malfunction in conventional vacuum systems[3]. This change in vacuum system greatly increases the efficiency of vacuum die casting process without any danger of malfunction.

Fig. 2 schematically shows the injection curve which

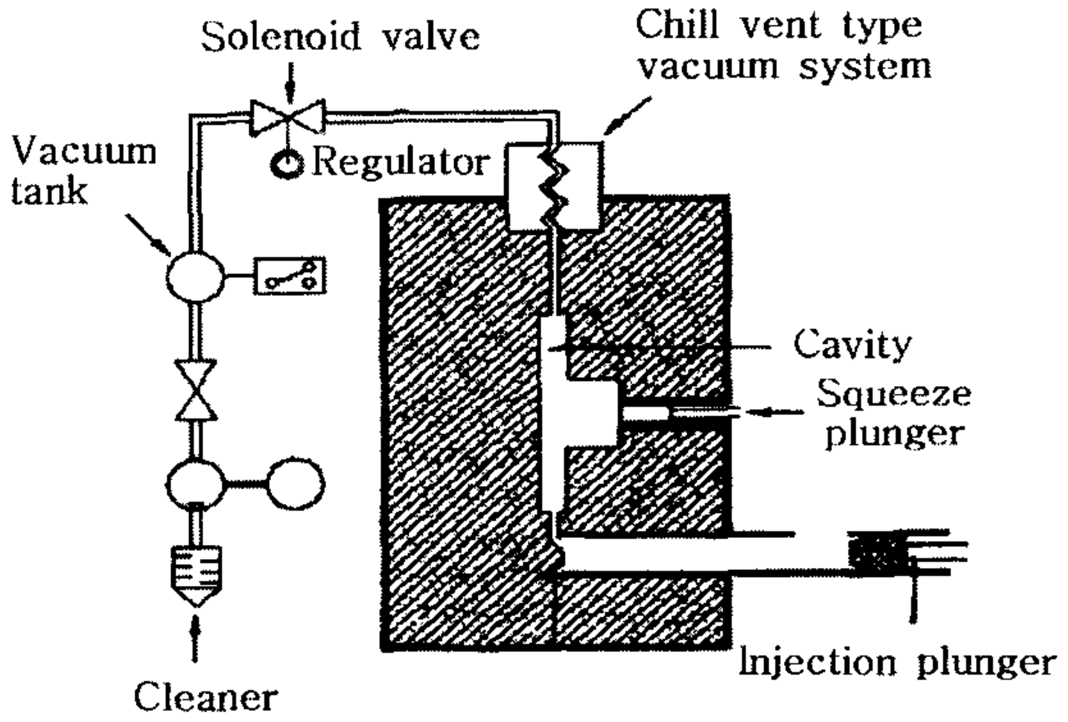


Fig. 1. Schematic drawing of partial squeeze and vacuum die casting machine

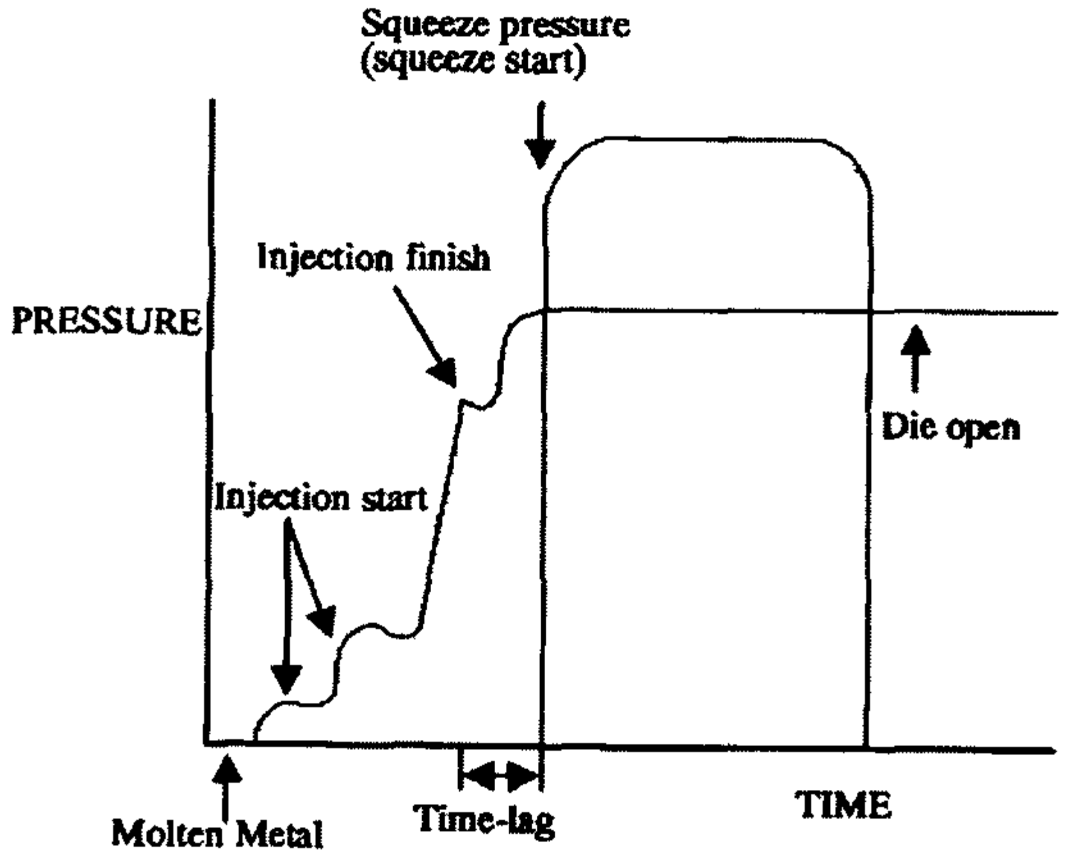


Fig. 2. Schematic drawing of injection curve.

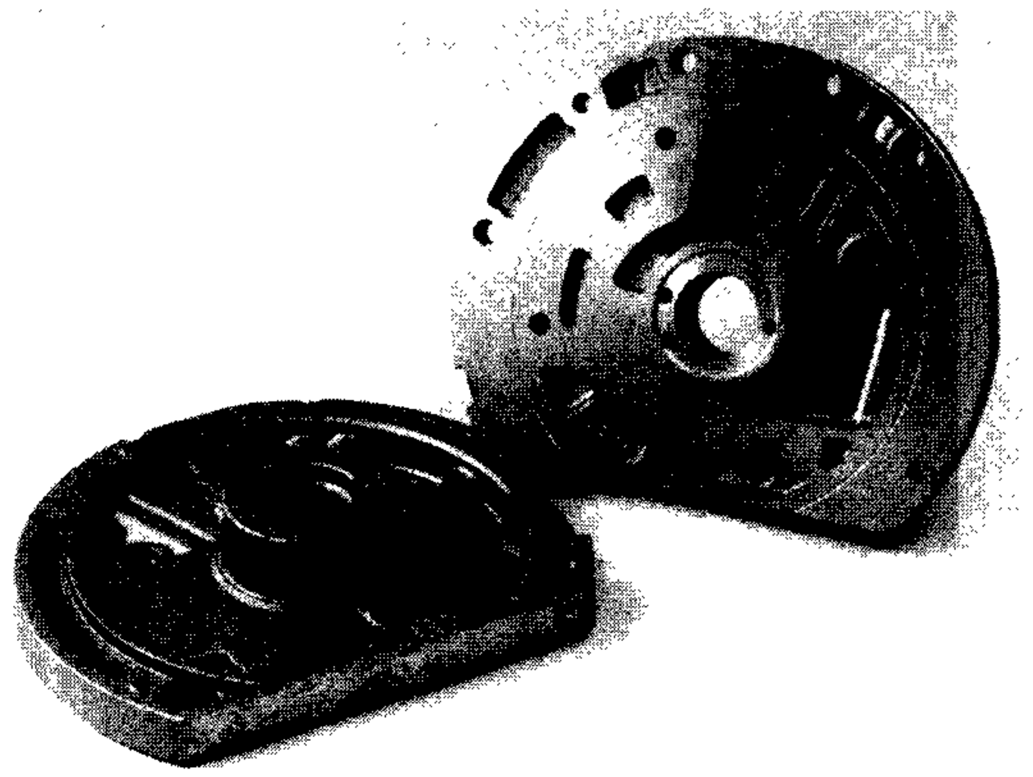


Fig. 3. Photograph of die cast trial product of reaction shaft support.

describes the injection time and squeeze pressure for the squeezing effect.

In this study, actual casting of reaction shaft support by using conventional die casting(CD), squeeze die casting(SD) and vacuum die casting(VD) were also performed respectively and compared with partial squeeze and vacuum die casting(SVD) to confirm the usefulness and reliability of the proposed process. Fig. 3 shows photograph of trial product of reaction shaft support.

The casting conditions for the reaction shaft support are summarized in Table 1.

Al-Si alloys are of particular value to the casting industry because of their high fluidity[8,9]. The high fluidity of Al-Si alloy imparted by the presence of relatively large volumes of the Al-Si eutectic. Other advantages of these castings are high resistance to corrosion and good weldability. Si also reduces hot shortness on freezing and reduces the coefficient of thermal expansion, whilst copper improves elevated temperature properties. However, machining may be difficult because of the presence of high Si particles in the microstructure. The hyper eutectic composition (above 12.7% Si) in this study, aims at high strength, wear resistivity and thermal resistivity to use as an automotive reaction shaft support. In this regard it is necessary to incorporate, in the eutectic matrix, sufficient quantities of hard primary silicon particles to provide high wear resistance and strength. It is also desirable to ensure that the primary silicon is well refined. For this, small amount of phosphorus was added to keep the size of primary Si within 10~50 μm which reacts with aluminum to form small, insoluble particles of Al-P that then serve as nuclei on which silicon forms. The modification was also performed by adding strontium. The addition of strontium as an Al-Sr or Al-Si-Sr master alloy produces a refined Al-Si eutectic. The alloy composition of Al-Si alloy in this study is shown in Table 2.

3. Results and Discussion

3.1 Die Casting Defect

Sectional views of reaction shaft support cast by conventional die casting (CD), squeeze die casting (SD), vacuum die casting (VD) and partial squeeze and

Table 1. Casting Conditions

Condition		CD	VD	SD	SVD
Pouring Temp., °C		700	700	700	700
Injection Pressure, kgf/cm^2		850	850	850	850
Injection Speed, m/sec	1st	0.30	0.30	0.30	0.30
	2nd	2.5	2.5	2.5	2.5
Squeeze Pressure, kgf/cm^2		-	-	1500~3000	1500~3000
Time-Lag, sec		-	-	0.5~2.0	0.5~2.0
Dwell time, sec		13	13	13	13
Cycle time, sec		65	65	65	65

Table 2. Chemical composition of hyper eutectic Al-Si alloy

Si	Cu	Mg	Zn	Fe	Mn	P	Al
14.5~15.5	4.0~5.0	0.5 ↓	0.5 ↓	0.8 ↓	0.2~0.3	0.06	bal.

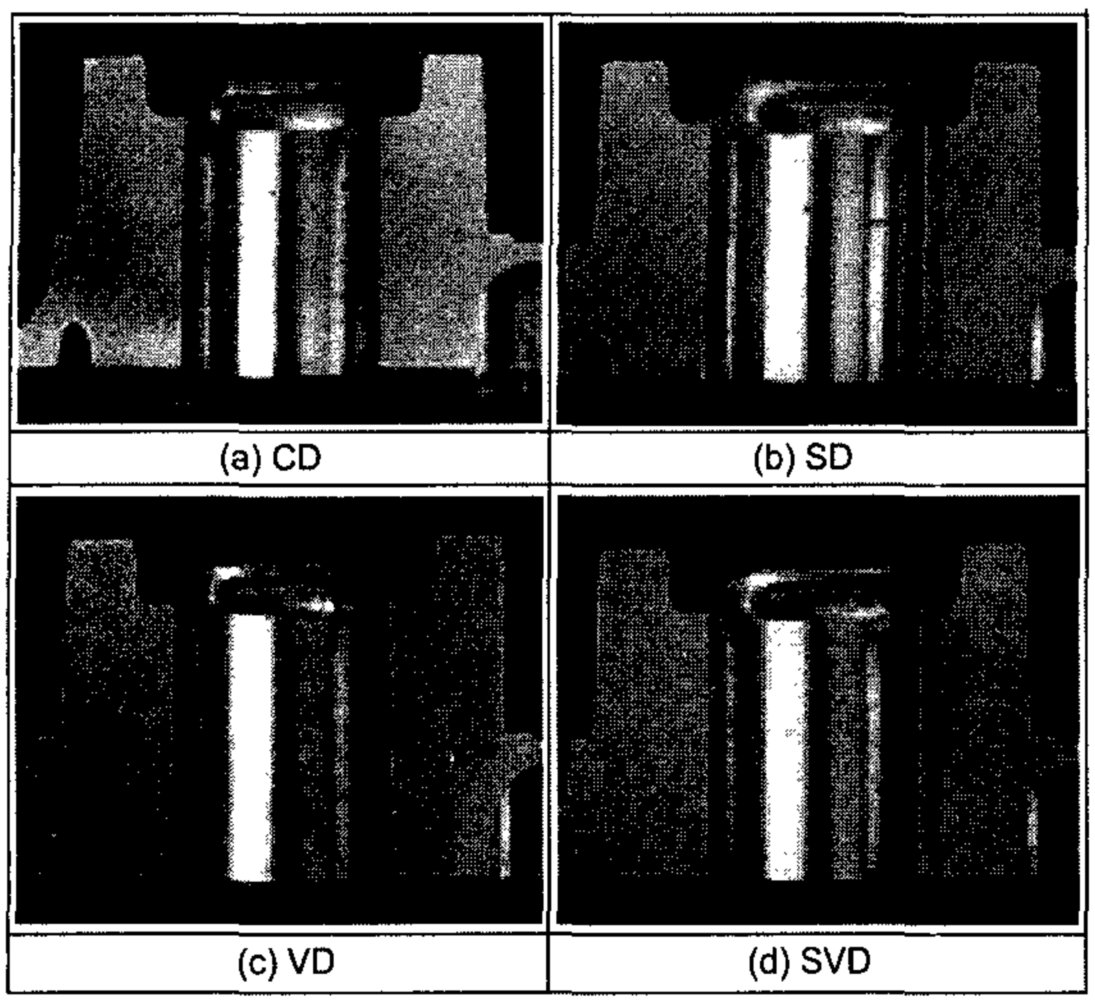

(a) CD
(b) SD
(c) VD
(d) SVD

Fig. 4. Photograph showing the sectional view of reaction shaft support.

vacuum die casting (SVD) are shown in Fig. 4.

In case of reaction shaft support cast by CD and SD, lots of porosity were formed especially at the thicker sections as shown in Fig. 4(a) and (b). Gas reactions due to the entrapped air in the mold cavity and the turbulences during injection partially intensifies the formation of porosity during casting. In the reaction shaft support cast by VD, the formation of porosity decreased significantly due to the removal of air in the mold cavity but the microdefects including to shrinkages were found as shown in Fig. 4(c). These local shrinkages during the VD process may be caused by difficulties in the supply of molten metal by the preferential dendritic solidification of molten metal at the injection gate. Because these kinds of casting defects are primarily originated by gas reactions and solidification shrinkages, the fundamental cure for these defects must be focused on the elimination of gas in the mold cavity and the pressurizing of casting products during solidification to compensate for the solidification shrinkages. As shown in Fig. 4(d), the partial squeeze and vacuum die casting method produced an almost defect free reaction shaft support. As explained before, the removal of gas by chill vent type vacuum system and squeezing pressure system during solidification satisfies the basic requirements for the prevention of casting defects.

3.2 Effect of Squeeze Pressure and Time Lag on Densification

To prevent casting defects such as shrinkage and porosity and more importantly, to improve mechanical properties of casting products, the effects of squeeze pressure and squeeze time lag on the densification of casting products were investigated. The degree of densification was estimated by the measurement of specific gravity. Fig. 5 shows the change in specific gravities measured by Electronic Densimeter (SD-120L).

In the case of a squeeze pressure of 1500 kgf/cm^2, the longer the squeeze time lag, the smaller the specific gravity. In the case of 3000 kgf/cm^2, the longer the squeeze time lag the larger the specific gravity until a time lag of 1.5 sec. At too low squeeze pressure of 1500 kgf/cm^2, the deformation resistance of the solidified layer which is estimated to be larger than the squeeze pressure restricts progressive stroke of the squeezing plunger. As time lag increases deformation resistance increases with increased solidified layer and this results in reduction of the squeezing effect due to the short plunger stroke. At too high squeeze pressure of 3000 kgf/cm^2, on the contrary, the squeezing pressure which is estimated to be larger than the deformation resistance of solidified layer enables unrestricted progress of squeeze plunger stroke. Therefore, the decrease in time lag results in progress of plunger to the squeeze plunger

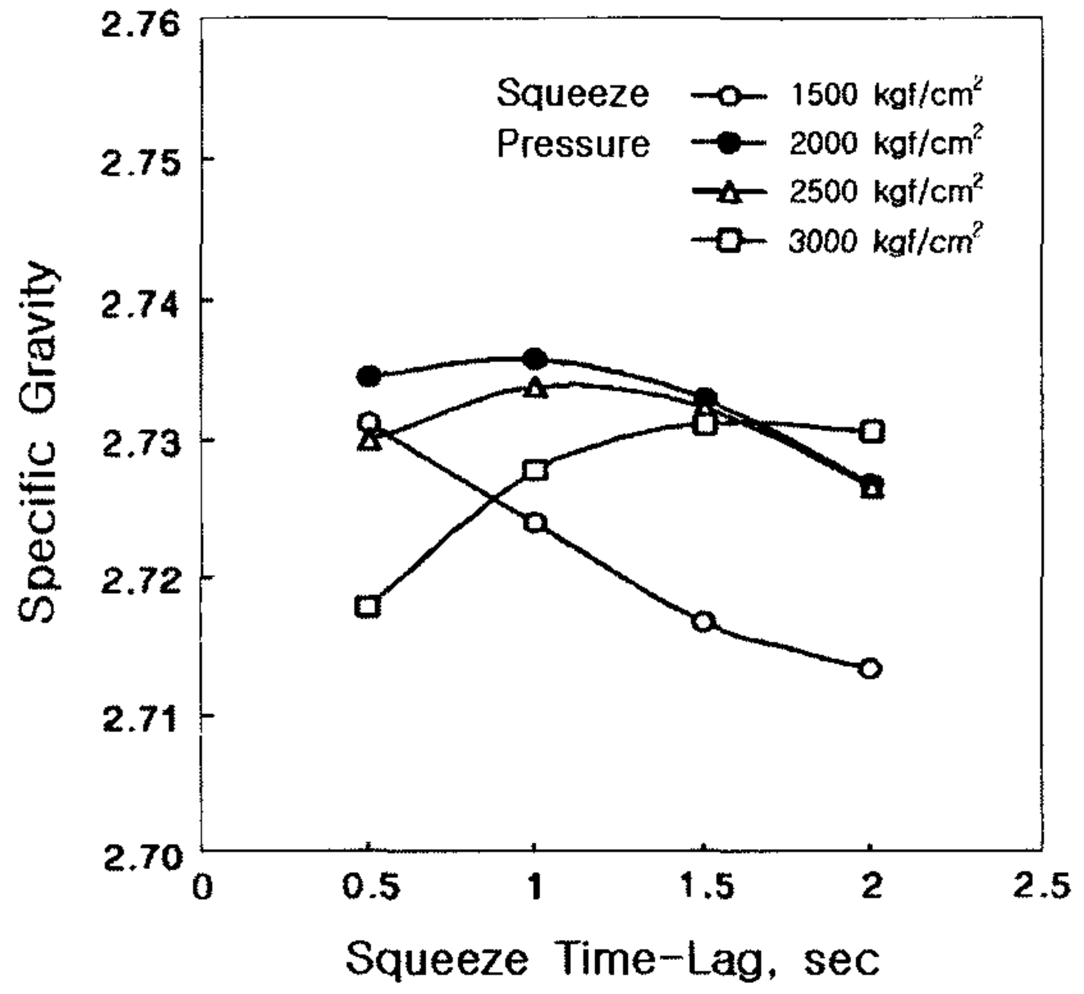


Fig. 5. The effect of squeeze pressure time lag on the specific gravity of cast products.

stroke end point in a moment and the sufficient squeezing effect can not be obtained during subsequent solidification. The reason for the decrease in specific gravity at the time lag of 2.0sec is that the deformation resistance of the solidified layer prevents the plunger stroke from reaching end stroke point. This insufficient squeeze pressure is responsible for the drop of specific gravity at larger time lag at 3000 kgf/cm^2.

In the squeeze pressure of 2000 kgf/cm^2 in Fig. 5, maximum specific gravity of 2.736 is obtained at the time lag of 1.0 sec. This good densification can also be explained by the relationship between plunger stroke and squeeze pressure as shown in Fig. 6.

In Fig. 6, the plunger stroke increases with increasing squeeze pressure and decreasing time lag. Therefore, squeezing effect can be increased by increasing squeezing pressure and decreasing time lag but too high squeeze pressure and too low time lag brought about insufficient squeezing effect due to instant movement to squeeze plunger stroke end point. Therefore an optimal squeeze condition can be achieved when the plunger stroke does not reach squeeze end point during solidification. Besides the global comparison of change in specific gravity with respect to squeeze pressure and time lag, local density variations in the cast product are also measured in this study. Fig. 7 shows X-ray photograph showing internal casting defects at different squeeze pressures and squeeze time-lags.

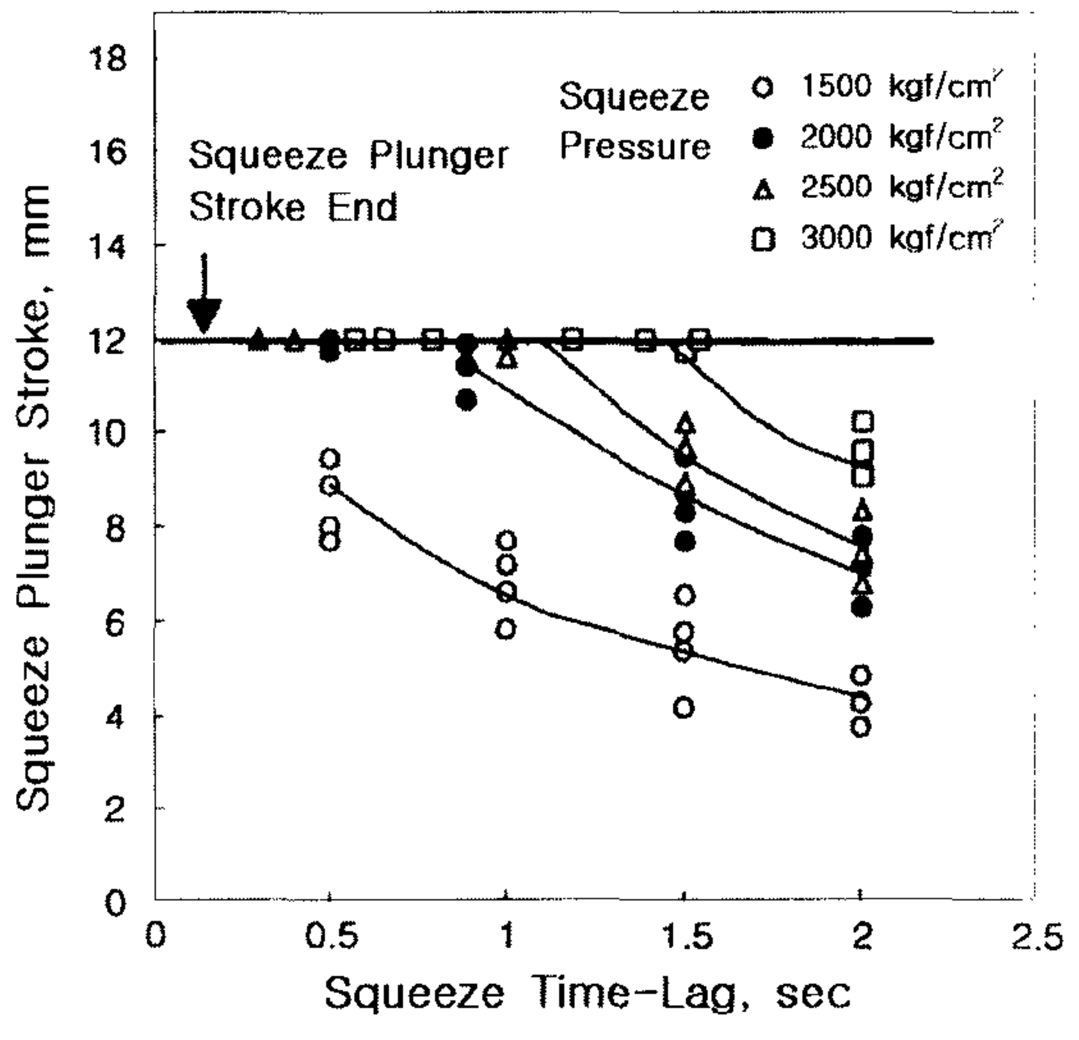
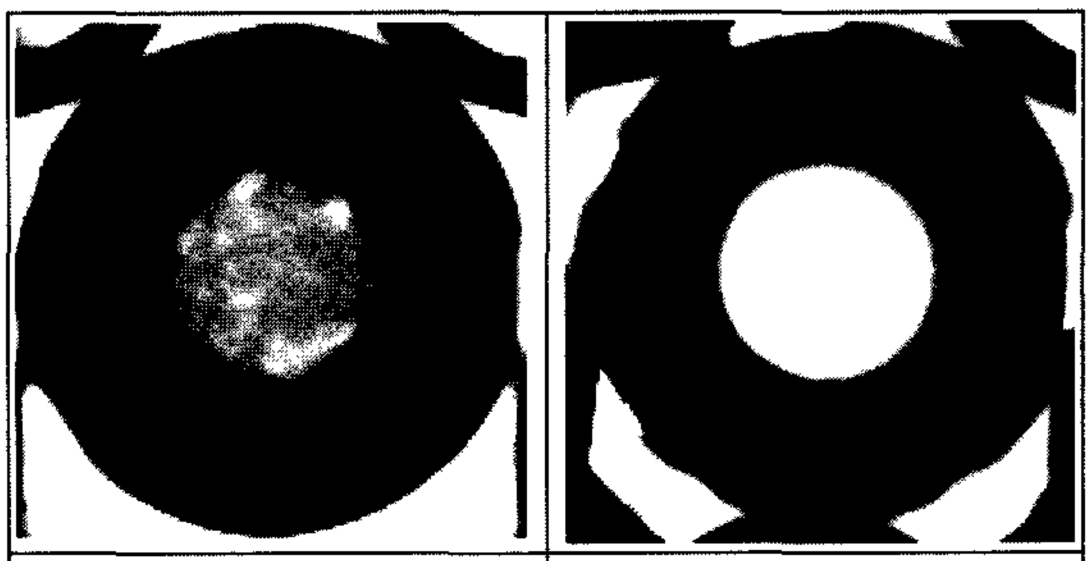
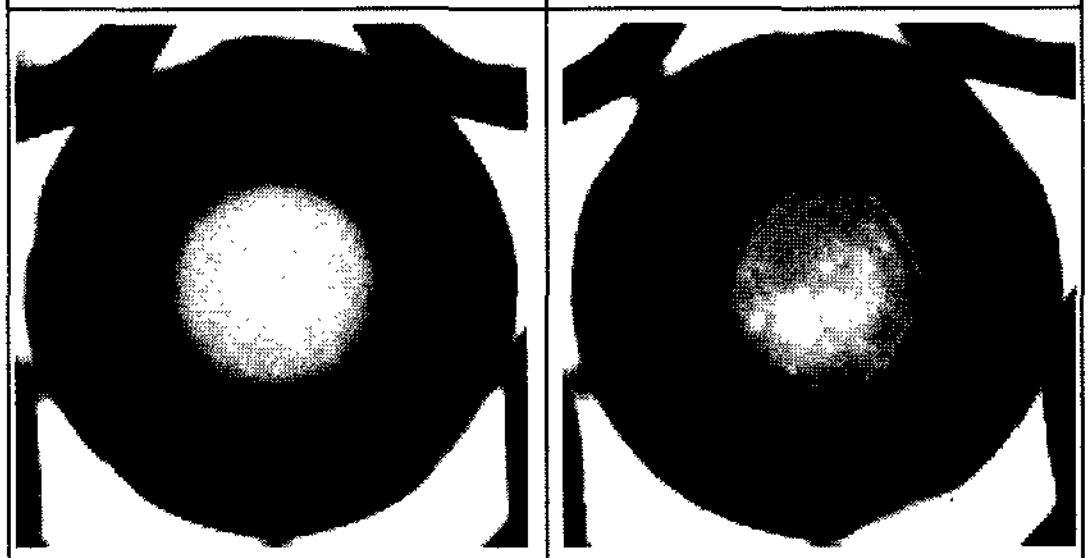


Fig. 6. The relationship between plunger stroke and squeeze time-lag.



(a) 1500 kgf/cm^2, 2.0sec

(b) 2000 kgf/cm^2, 2.0sec



(c) 2500 kgf/cm^2, 1.0sec

(d) 3000 kgf/cm^2, 0.5sec

Fig. 7. X-ray radiograph showing internal casting defects at different squeeze pressures and squeeze time-lags:

After sectioning the cast reaction shaft support in rectangular shapes and the specific gravity was measured piece by piece. The measured specific gravity of each piece was compared with that of squeezing point. When the measured specific gravity of a piece is similar to that of squeezing point (within ±0.2%), then the region of that piece is marked by hatching lines as shown in Fig. 7 and if lower than that of partial squeezing point, then it remains white. At the longer time lag such as 1.5 and 2.0 sec, the denser parts are restricted to the vicinity of squeezing point but with decreasing time lag the densification spread uniformly along sections of products. From this, the maximum densification at 2000 kgf/cm^2 and time lag of 1.0 sec in Fig. 5 can be achieved only when the uniform and full densification along all the sections of products are obtained.

3.3 Mechanical Properties

The mechanical properties of die cast products obtained by various process are compared in Table 3.

In most engineering materials, the strength of material

Table 3. Mechanical properties of die cast products

Specimen condition	Yield strength, kgf/cm^2	Tensile Strength, kgf/cm^2	Elongation, %	Hardness, Hv	Specific Gravity
CD	10.8	16.94	0.15	123	2.715
VD	12.7	23.23	0.20	127	2.730
SD	11.5	19.74	0.19	130	2.731
SVD	13.9	24.92	0.26	133	2.736

is mainly dependent on the microstructure. In view of tensile properties, SVD shows highest tensile strength and elongation. This implies that the microstructural soundness of SVD provides the best mechanical properties when compared to other die casting processes.

Intensive microstructural analysis shows that the non-uniform dendritic structures and segregations of primary Si are widely observed except in microstructures obtained from SVD process. Gas entrapment, turbulent flow and insufficient squeeze pressure might be responsible for these kinds of microstructure. In case of the SVD process, the combination of vacuum effect and squeezing effect enables defect free products and the primary Si particles having 10~30 μm diameter which an provide wear-resistivity and heat-resistivity are observed to be uniformly distributed. This can be explained by the change in transformation temperature due to squeeze pressure. The increase in squeeze pressure may make possible an increase of the Si solubility in the aluminum matrix and result in refinement of primary Si particles.

Fig. 8 shows the microstructural change at various die casting processes. As shown in the figure, uniform distribution of fine acicular eutectic and primary Si, which is the primary factors for the best mechanical properties, can be obtained by squeeze and vacuum die casting.

In summary, the CD process would be partially improved by VD, SD, but the best casting qualities and mechanical properties were obtained by SVD process which was estimated to be most feasible process.

4. Conclusion

From the studies on the hybrid technique of squeeze casting with vacuum die casting to make a automobile part, followings are concluded;

1) Excellent defect free die casting products would be made by the optimal combination of vacuum effect before injection and partial squeezing after injection

2) Cast products by SVD have fine and uniform microstructure and show excellent mechanical properties

3) In SVD, the time lag for the maximum densification must be increased with squeeze pressure and the optimum squeeze condition would be achieved when the plunger stroke did not reach squeeze end point during the solidification.

Reference

[1] M. Yokoi, K. Fujii and K. Nishihawa : Transactions of Japanese Die Casting Congress, "Development of runner local squeeze for die casting, castings",(1996), 197-203.

[2] T. Kan and T. Uehara : Japan Light Metals Press Co., "Die casting of aluminum alloy", (1988), 438-445.

[3] Japan Die Casting Association, Light metal communication Co., "Technical history of die casting",(1995), 11-18.

[4] T. Komazoki and N. Nishi : Transactions of Japanese Die Casting Congress, "Solidified structure of Aluminum die casting", (1990), 119-125.

[5] K. Fukizawa and H. Shiina : J. of the Society of Automotive Engineers of Japan, "The weight reduction of automobile engine using aluminum alloys", Vol.46, No.5(1992), 66-72.

[6] M. Okayasu, N. Nishi and K. Komazana : Transactions of Japanese Die Casting Congress, "Effects of casting defects on mechanical properties of aluminum die castings", 1998, 165-172.

[7] Metals Handbook, ASM, 9th Edition, Vol.15 (1988), 204-210.

[8] I. J. Polmear : Edward Arnold Co., "Light Alloys-metallurgy of the light metals", UK, 1981.

[9] Frank King, John Wiley & Sons : New York, "Aluminum and Its Alloys", 1987.