ELSEVIER

Journal of Materials Processing Technology 105 (2000) 42–48

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

A feasibility study of the partial squeeze and vacuum die casting process

E.S. Kim[a], K.H. Lee[b], Y.H. Moon[c,*]

[a]R & D Division, Dong Nam Precision Company Ltd., Ulsan, South Korea
[b]Department of Materials and Metallurgical Engineering, University of Ulsan, Ulsan, South Korea
[c]Engineering Research Center for Net Shape and Die Manufacturing, Pusan National University, Pusan, South Korea

Received 16 January 1999

Abstract

A feasibility study of the partial squeeze and vacuum die casting process was performed to make defect-free casting products with excellent mechanical properties. The trial die casting process in this study was industrially implemented for producing a reaction shaft support made of a hyper eutectic Al–15%Si alloy. To combine the squeezing and vacuum effect, the plunger injection system was designed and attached to a chill vent type vacuum machinery system. The combination of the vacuum effect before injection and the squeezing effect after injection resulted in excellent defect-free die casting products. The uniform distribution of fine acicular eutectic and proeutectic silicon obtained from the trial process also provided excellent mechanical properties. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Partial squeeze and vacuum die casting; Hypereutectic Al–Si alloy; Squeeze pressure; Plunger stroke; Injection pressure; Injection speed

1. Introduction

Recently the manufacturing of aluminum alloys for use in several casting processes has for many different reasons become a topic of prime importance to many researchers [1–3]. This development has been primarily set in motion by the need to save energy by using lightweight materials in the field of transport and also because of the pressure of the constantly increasing requirement of functionality and quality. Of equal importance are the demands for more rational production techniques with regard to the protection of the environment. The die casting of aluminum alloys can fulfill this wide range of requirements in a special way when compared with other materials and production processes.

Die casting injects the liquid metal into permanent molds at high speed. This means low cycle times and accurate castings of good surface quality. Therefore die casting is ideally suited for producing small near net shape artifacts that require good surface texture 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 cannot 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. However, 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 in the molten metal and despite the applied pressure high levels of porosity are produced as the relatively narrow gate solidifies before the bulk of the casting. Controlled injection can reduce air entrapment but porosity is still produced if the casting is not fed properly. Several modifications to pressure die casting have been developed to increase the integrity of pressure die castings. In the ACCURAD process [4], 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 allow feeding. The secondary plunger

* Corresponding author.: Tel.: +82-51-510-2472;
fax: +82-51-512-1722.
E-mail address: yhmoon@hyowon.pusan.ac.kr (Y.H. Moon).

0924-0136/00/$ – see front matter
PII: S0924-0136(00)00557-4

operates typically for 0.1–1.5 s after the main plunger, depending on the size of the casting. However, the lower velocities generated by the larger gate reduce fluidity so that castings cannot be as complex or thin walled as in conventional high pressure die casting. An alternative approach is used in pore free die casting [5], 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 <1 μm), thus reducing porosity. The 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, the production rates are reduced. The gas free vacuum die casting process [6] reduces the air pressure (to below 200 mm Hg) inside the mold just before the injection of molten metal, 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. However, the precise control and maintenance of the shut on/off vacuum valve attached to the die limits production rates. Squeeze casting [7] 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, as parts can be made to near net shape, with complex shapes and fine surface detail. However, as the cycle time is increased to allow the squeezing effect, the production rates are reduced and the production costs are increased due to the squeezing machinery.

Therefore, in this feasibility study, an advanced die casting technique to satisfy high productivity (the zero vacuum die casting method) and high quality (controlling porosity and shrinkage) is industrially implemented to produce reaction shaft support using hyper eutectic Al–Si alloy. The hybrid technique of partial squeeze casting with vacuum die casting in this study shows excellent productivity and casting qualities when compared with other die casting processes.

2. Procedure

2.1. Alloy design of Al–15%Si hyper eutectic composition

Aluminum–silicon alloys are of particular value to the casting industry because of their high fluidity [8,9] being imparted by the presence of a relatively large volumes of the Al–Si eutectic. Other advantages of these castings are high resistance to corrosion and good weldability. Silicon also reduces hot shortness on freezing and reduces the coefficient of thermal expansion, whilst copper improves elevated temperature properties. However, machining may present difficulties because of the presence of high silicon particles in the microstructure. The hyper eutectic composition (above 12.7%Si) in this study aims at high strength, wear resistivity and thermal resistivity in 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 impart strength. It is also desirable to ensure that the primary silicon is well refined. For this, a small amount of phosphorus is added to keep the size of the proeutectic Si to 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 is 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 1.

Table 1
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	Val.

2.2. System design for hybriding squeeze casting with vacuum die casting

The machinery for making a hybrid of partial squeeze casting and vacuum die casting is shown schematically in Fig. 1. As shown therein a chill vent type vacuum system is adopted in this study. The spontaneous shutting-off effect due to early solidification of the leading molten metal at the chill vent zone no longer needs the installation of a shut-off valve, which has been the main cause of malfunction in the conventional vacuum system [6]. This change in vacuum system greatly increases the efficiency of the vacuum die casting process without any danger of malfunction. Fig. 2 shows schematically the injection curve which describes the injection time and squeeze pressure for the squeezing effect.

In this study, the actual casting of a reaction support shaft using conventional die casting (CD), squeeze die casting (SD) and vacuum die casting (VD) are performed and compared with partial squeeze and vacuum die casting (SVD) to confirm the usefulness and reliability of the proposed process. Fig. 3 shows photographs of trial product of a reaction shaft support. The casting conditions for the reaction shaft support are summarized in Table 2.

3. Results and discussion

3.1. Die casting defect

Sectional views of the reaction shaft support cast by CD, SD, VD and SVD are shown in Fig. 4. In the case of the

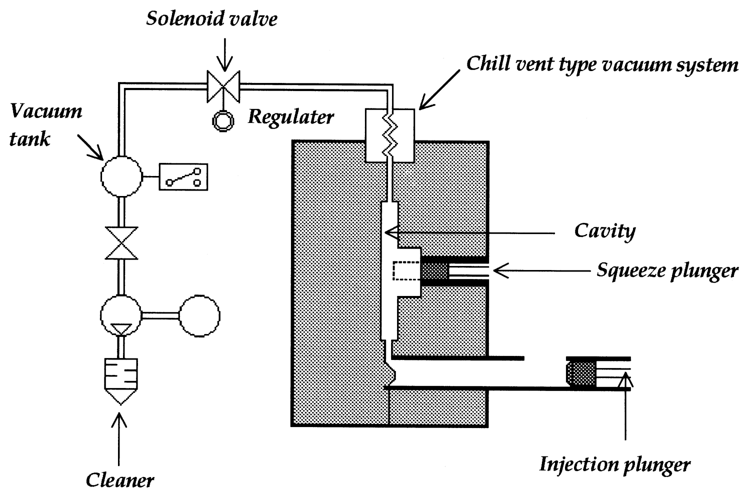

Fig. 1. Schematic drawing of the partial squeeze and vacuum die casting machinery.

reaction shaft support cast by CD and SD, a lot of porosity is formed, especially at the thicker sections, as shown in Fig. 4a and b. Gas reactions due to the entrapped air in the mold cavity and the turbulence during injection partially intensify the formation of porosity during casting. As for the reaction shaft support cast by VD, the formation of porosity is significantly prevented because of the removal of air in the mold cavity, but microdefects due to shrinkage are found, as shown in Fig. 4c. This local shrinkage 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. 4d, the partial squeeze and vacuum die casting method produces an almost defect-free reaction shaft support. As explained before, the removal of gas by the chill vent type vacuum system and the squeezing pressure system during solidification satisfies the basic requirements for the prevention of casting defects.

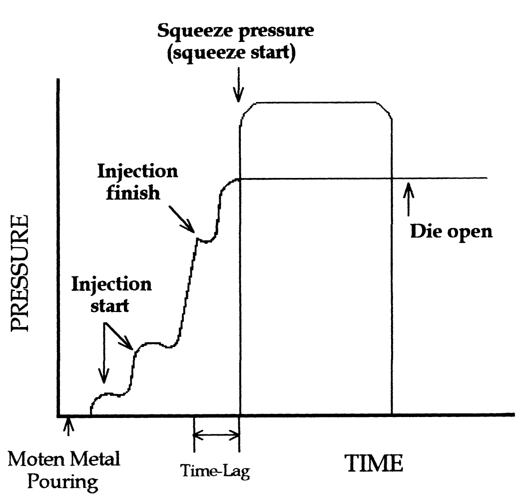

Fig. 2. Schematic drawing of the injection curve.

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 the mechanical properties of cast products, the effects of the squeeze pressure and the squeeze time lag on the densification of the cast products are investigated. The degree of densification is estimated by the measurement of specific gravity. Fig. 5 shows the change in specific gravity measured by an Electronic Densimeter (SD-120L).

In the case of a squeeze pressure of 1500 kg/cm^2, the longer the squeeze time lag, the smaller the specific gravity. In the case of 3000 kg/cm^2, the longer the squeeze time lag the larger the specific gravity until a time lag of 1.5 s. At too low a squeeze pressure, 1500 kg/cm^2, the deformation resistance of the solidified layer, which is estimated to be

Table 2
Casting conditions

Condition	OD	VD	SD	SVD
Pouring temperature (°C)	700	700	700	700
Injection pressure (kg/cm^2)	850	850	850	850
Injection speed (m/s)				
First	0.30	0.30	0.30	0.30
Second	2.5	2.5	2.5	2.5
Squeeze pressure (kg/cm^2)	–	–	1500–3000	1500–3000
Time lag	–	–	0.5–2.0	0.5–2.0
Dwell timd (s)	13	13	13	13
Cycle time (s)	65	65	65	65

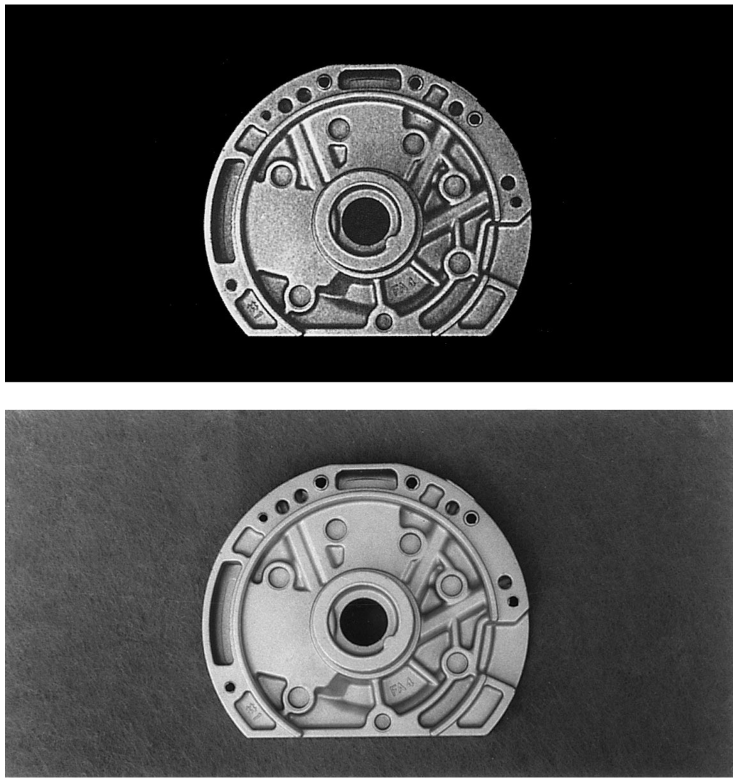

Fig. 3. Photographs of the die cast trial product of a reaction shaft support.

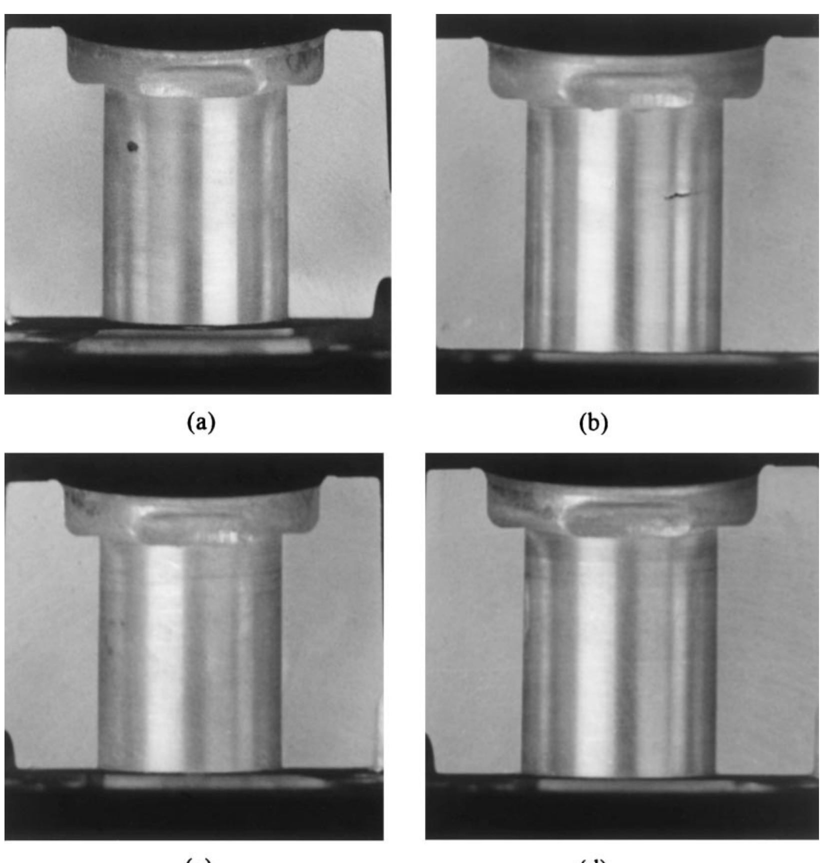

Fig. 4. Photographs showing sectional views of the reaction shaft support: (a) CD; (b) SD; (c) VD; and (d) SVD.

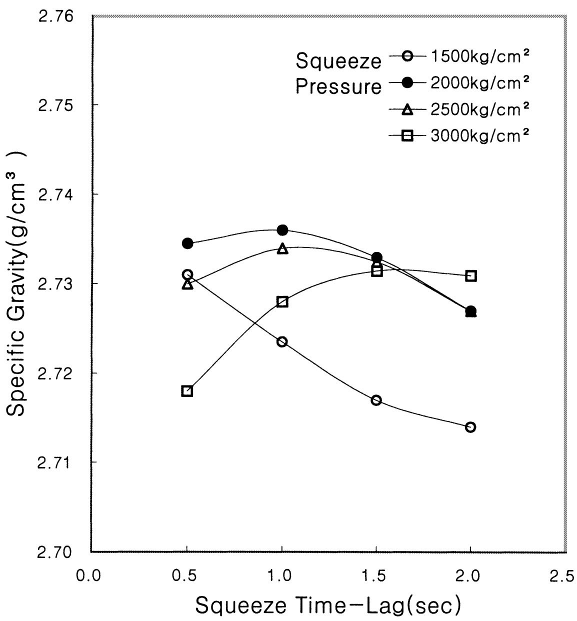

Fig. 5. The effect of the squeeze pressure and time lag on the specific gravity of cast products.

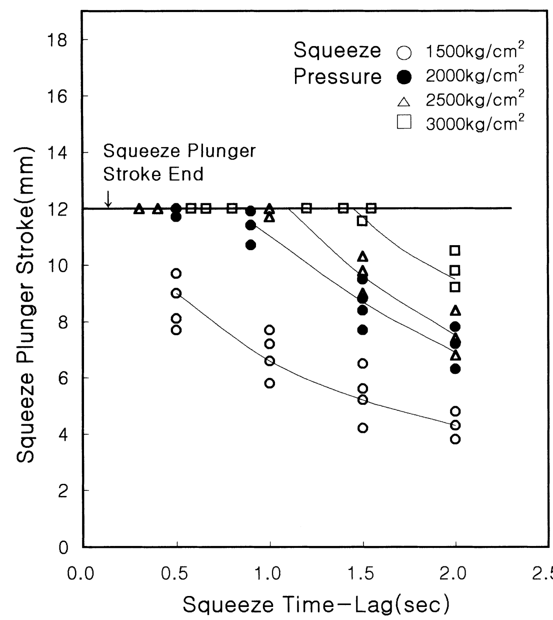

Fig. 6. The relationship between plunger stroke and squeeze pressure.

larger than the squeeze pressure, restricts the progressive stroke of the squeezing plunger. As the time lag increases, the deformation resistance is increased with an increased solidified layer and this results in squeezing effect decreasing due to the shorter plunger stroke. At too high a squeeze pressure, 3000 kg/cm^2, on the contrary, the squeezing pressure, which is estimated to be larger than the deformation resistance of the solidified layer, enables unrestricted progress of the squeeze plunger stroke. Therefore the decrease in time lag results in progress of plunger to the squeeze plunger stroke end point in a short time and sufficient squeezing effect cannot be obtained during subsequent solidification. The reason for the decrease in specific gravity at the time lag of 2.0 s is that the deformation resistance of the solidified layer prevents the plunger stroke from reaching the end stroke point. This insufficient squeeze pressure is

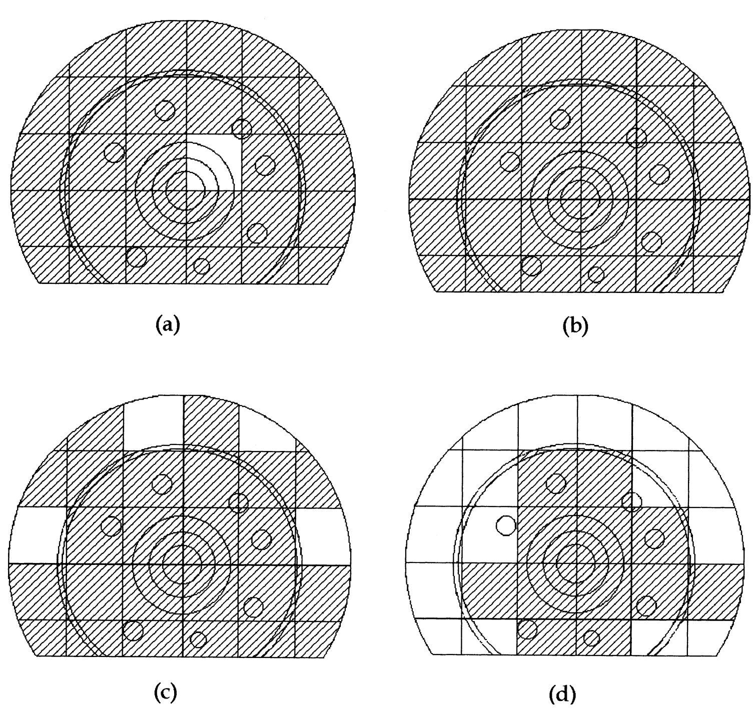

Fig. 7. Local density variation at a squeeze pressure 2000 kg/cm^2 and a time lag of: (a) 0.5 s; (b) 1.0 s; (c) 1.5 s; and (d) 2.0 s.

Table 3
Mechanical properties of the die cast procucts

Specimen condition	Yield strength (kg/cm^2)	Tensile strength (kg/cm^2)	Elongation (%)	Hardness (Hv)	Specific gravity (g/cm^2)
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

responsible for the drop of specific gravity at a larger time lag at 3000 kg/cm^2.

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

In Fig. 6, the plunger stroke is increased with increasing squeeze pressure and decreasing time lag. Therefore, the squeezing effect can be increased by increasing the squeezing pressure and decreasing the time lag but too high a squeeze pressure and too low a time lag brought about insufficient squeezing effect due to instant movement to the squeeze plunger stroke end point. Therefore an optimal squeeze condition can be achieved when the plunger stroke does not reach the squeeze end point during solidification. In addition to 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 the local density variation at a squeeze pressure of 2000 kg/cm^2 with time lags of 0.5, 1.0, 1.5 and 2.0 s.

After sectioning the cast reaction shaft support in a rectangular manner, the specific gravity is measured piece by piece. The measured specific gravity of each piece is compared with that of the 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

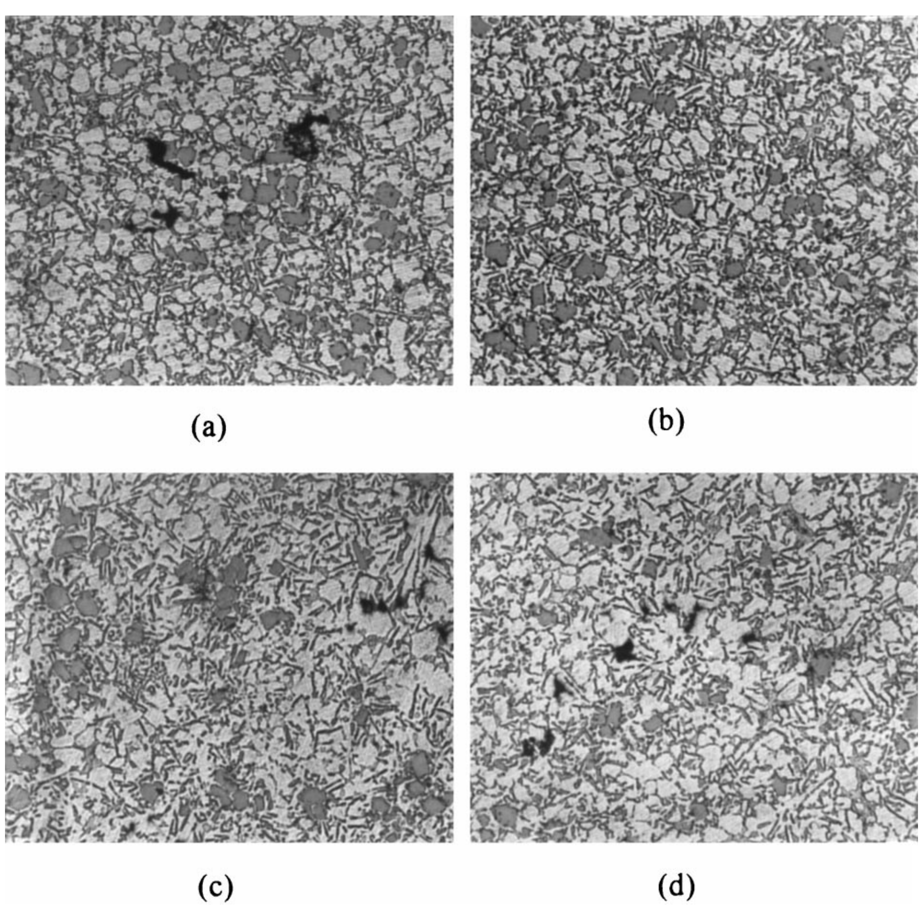

Fig. 8. Typical microstructure at various squeeze pressures (time lag=1.0 s): (a) 1500 kg/cm^2; (b) 2000 kg/cm^2; (c) 2500 kg/cm^2; and (d) 3000 kg/cm^2.

piece is marked by hatched lines in Fig. 7 and if lower than that of the partial squeezing point, then it remains white. At longer time lags such as 1.5 and 2.0 s, the denser parts are restricted to the vicinity of the squeezing point but with decreasing time lag the densification spreads uniformly along the sections of the product. From this, it can be inferred that the maximum densification at 2000 kg/cm^2 and time lag of 1.0 s in Fig. 5 can be achieved only when uniform and full densification along all the sections of the products is obtained.

3.3. Mechanical properties

The mechanical properties of the die cast products obtained by various processes are compared in Table 3. In most engineering materials, the strength of the material is largely 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 non-uniform dendritic structures and segregations of proeutectic silicon are widely observed except in the microstructures obtained from the SVD process. Gas entrapment, turbulent flow and insufficient squeeze pressure might be responsible for these kinds of microstructure. In the case of the SVD process, the combination of the vacuum effect and the squeezing effect enables defect-free products, and proeutectic Si particles having 10–30 μm diameter, which can provide wear resistivity and heat resistivity, are observed to be uniformly distributed. This can be explained by the change in transformation temperature due to the squeeze pressure. The increase in squeeze pressure may lead to an increase in the silicon solubility in the aluminum matrix and result in refinement of proeutectic silicon particles.

Fig. 8 shows the microstructural change with respect to change in squeezing pressure. In the case of low squeezing pressure (Fig. 8a), as the higher deformation resistance of solidified layer restricts the plunger stroke, destruction of the aluminum dendritic structure and eutectic is relatively small and microdefects are formed. In case of higher squeeze pressure, Fig. 8c and d, too short a squeezing time due to high pressure prevents sufficient destruction of the dendritic structure and some microdefects are formed. In case of 2000 kg/cm^2, the microstructure is characterized by fine eutectic and uniformly distributed proeutectic Si.

Therefore, uniform distribution of fine acicular eutectic and proeutectic Si are the primary factors for the best mechanical properties. In summary, the CD process can be partially improved by VD and SD, but the best casting qualities and mechanical properties can be obtained by the SVD process, which is considered to be the most feasible process.

4. Conclusions

This feasibility study of the hybrid technique of squeeze casting with vacuum die casting was performed to make defect-free casting products having excellent mechanical properties. The results of this study are as follows:

1. the combination of the vacuum effect before injection and partial squeezing after injection provided excellent defect-free die cast products;
2. the cast products produced by SVD have a 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 can be achieved when the plunger stroke does not reach the squeeze end point during solidification.

References

[1] K. Fukizawa, H. Shiina, J. Soc. Auto. Eng. Jpn. 46 (5) (1992) 66.
[2] D.O. Kennedy, Mod. Cast. 2 (1992) 34.
[3] Metals Handbook, Vol. 15, 9th Edition, ASM, New York, 1988, p. 204.
[4] L. Maclaren, Die Cast. 31 (1967) 7.
[5] T. Kan, T. Uehara, Die Casting of Aluminum Alloy, Japan Light Metals Press Co., Japan, 1988, p. 438.
[6] Technical History of Die Casting, Japan Die Casting Association, Light Metal Communication Co., Japan, 1995, p. 11.
[7] R.F. Lynch, R.P. Olley, P.C.J. Gallagher, AFS Transactions Paper No. 75–122, 1975, p. 569.
[8] I.J. Polmear, Light Alloys — Metallurgy of the Light Metals, Arnold, UK, 1981.
[9] F. King, Aluminum and its Alloys, Wiley, New York, 1987.