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Squeeze casting of magnesium alloys and their composites

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Squeeze casting, also known as liquid metal forging, extrusion casting and pressure crystallization, is a process in which molten metal soldifies in a die under an applied high pressure. The concept of squeeze casting was invented in Russia over 100 years ago. Later the process was exploited in North America, Japan and Europe to produce various automotive components. With the rapid expansion of magnesium applications in the automotive industry, the development of squeeze-casting technology for magnesium alloys and their composites has been motivated by incentives to produce high-quality components. The present paper reviews recent progress in squeeze casting, and the effects of process variables on the cast structure and properties of magnesium alloys and magnesium-based composites. Approaches to optimization of the squeeze-casting process are discussed. The significant advantages of squeeze-cast magnesium alloys and magnesium-based composites are highlighted. The on-going research work at ITM is presented. © *1998 Chapman & Hall*

1. Introduction

Squeeze casting is a process which involves the solidification of a molten metal in a closed die under an imposed high pressure. Other terms used to describe the same or similar processes are liquid metal forging, extrusion casting and pressure crystallization. The high applied pressure, which is several orders of magnitude greater than the melt pressure developed in normal casting processes, keeps entrapped gases in solution and squeezes molten metal from hot spots to incipient shrinkage pores. As a result, the porosity in a squeeze-cast component is almost eliminated. Furthermore, due to the elimination of the air gap at the liquid–mould interface by the applied high pressure, the heat transfer across die surfaces is enhanced, which increases solidification and cooling rates. Thus, superior mechanical properties of the casting resulting from the pore-free fine microstructure are achieved in squeeze-casting processes.

The concept of squeeze casting was originally introduced in 1819 via a British Patent [1] and further envisioned by a Russian, Chernov [2] in a report. However, it was not until 1931 that the first squeeze-casting experiment was scientifically carried out in Germany [3] on Al–Si alloy. During the late 1930s, the detailed investigation of squeeze casting of brass and bronze cylinders was initiated in Russia. Following extensive work on various ferrous and non-ferrous metals and alloys [4–8], the process variables dictating the technique were established, and by the mid 1960s, 150 large batch plants were in operation in Russia to produce 200 different types of squeeze-cast components. Meanwhile, Uram *et al.* [9], who may be the earliest Americans to study the effect of pressure on the solidification of metals, reported in the 1950s that, by applying a gas pressure of 1.7 MPa to an aluminium alloy during its solidification, the amount of microporosity was reduced. However, their results indicated that the reduction in porosity was not accompanied by any improvement in the mechanical properties. The reason for this was that the level of applied pressures was considerably lower compared to 100 MPa normally used nowadays. In the early 1960s, two Americans, Resis and Kron [10], conducted the first squeeze-casting experiment in North America, in which very high pressures of 340 and 690 MPa were used. They revealed an appreciable increase in the mechanical properties. Unfortunately, these pressure levels were too high to be easily implemented in production. In 1965, an English translation of Plyatskii's authoritative book [11] appeared to awaken Western interest in squeeze casting. Since then, numerous research activities and commercial developments of squeeze casting have taken place in North America, Japan and Europe. The bulk of the work in the West has focused on aluminium alloys, copper alloys, cast iron, stainless steel and nickel-based superalloys [12–30]. This process has been successfully applied to the manufacture of aluminium automotive components such as wheels, engine blocks, pistons and disc brakes. Recently, more interest has been expressed in the production of metal matrix composites using the

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squeeze-casting technique. Especially, extensive work on aluminium-based composites has been done. As a result, various aluminium-based reinforced components have been produced and are being used commercially [31–43].

In the past few years, with the rapid expansion of magnesium applications in the automotive industry, the development of squeeze-casting technology for magnesium alloys and their composites has been motivated by incentives to produce high-quality components. Although a number of research activities [23, 44–52] have taken place, few applications of squeeze-cast magnesium and its composite components have been reported in the open literature. This article reviews recent progress in squeeze casting of magnesium alloys and magnesium-based composites. The effects of process variables on the cast structure and properties of magnesium alloys and magnesium-based composites are discussed. The significant advantages of squeeze-cast magnesium alloys and magnesium-based composites are highlighted. The on-going research work at the Institute of Magnesium Technology (ITM) is presented.

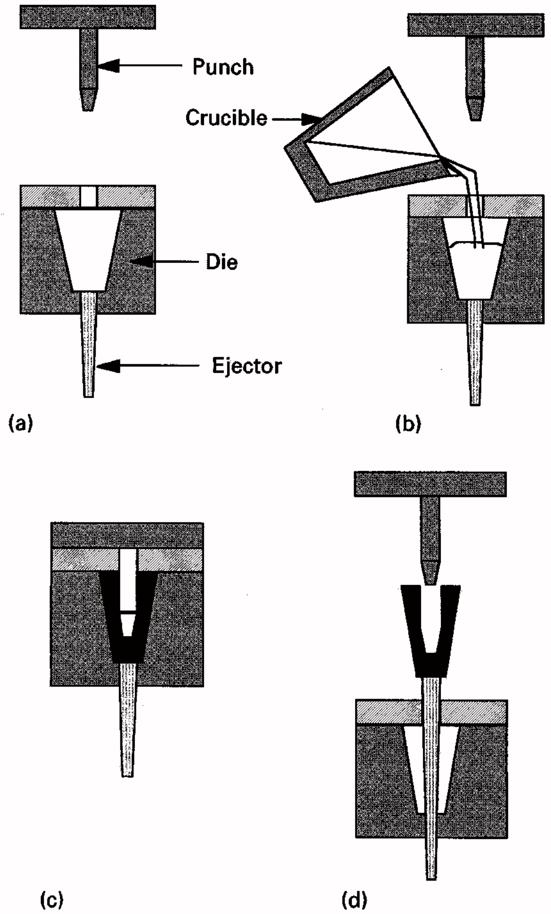

Figure 1 Schematic diagram of the direct squeeze-casting process. (a) Step 1, preheat, lubricating tooling. (b) Step 2, transfer melt into die cavity. (c) Step 3, solidify melt under pressure. (d) Step 4, eject casting.

2. Squeeze-casting processes

Squeeze casting has been developed based on the principle of pressurized solidification, in which finished castings can be produced in a single process from molten metal to solid components within re-usable dies. The process which is schematically shown in Fig. 1 involves several steps.

1. A suitable dieset is installed on the bed of a hydraulic press. The dieset is preheated to a required working temperature. During the heating-up period, the dieset is usually sprayed with a commercial graphite lubricant.
2. A metered quantity of molten metal is poured into an open female die cavity. Then, an upper male die or punch is lowered, coming into contact with the liquid metal.
3. The pressure is applied shortly after molten metal begins to solidify and is maintained until all the molten metal has solidified.
4. The upper punch returns to its original position and the casting is ejected.

In general, two different kinds of squeeze-casting techniques, known as "direct" and "indirect", have been developed based on different approaches of metal metering and metal movement. The direct squeeze-casting technique is characterized by a direct pressure imposed on to the casting without any gating system, as illustrated in Fig. 1. Because the pressure is directly applied to the entire surface of the molten metal during solidification, this technique gives fully densified components and extremely fast heat transfer which yields fine grain structure. As a result, higher mechanical properties are attained. In the indirect technique, as shown in Fig. 2, however, the pressure is exerted on a gate which transmits the load to the component. Owing to the fact that the pressure is imposed at a distance from the component, it is difficult to maintain a high pressure on the component throughout its solidifying and cooling periods. This indicates that it is difficult to cast long freezing range alloys with the indirect technique. Also, metal yield is much lower than that achievable with direct squeeze casting, owing to the necessity of using a gating system. The advantage of the indirect technique is that, due to the presence of a gating system, a highly accurate external metering system is not necessary. Variations in metal volume are adjusted in the gate. Although it seems that the direct technique offers more opportunities for a wide range of alloys to be used for the production of high-strength, full-integrity metal casting and metal matrix composite components that is the philosophy of squeeze casting, more indirect than direct squeeze-casting machines are in operation at present. This is probably because the indirect process has successfully been commercialized.

3. Effects of process parameters

For both direct and indirect squeeze castings, there are a number of parameters that generally influence the soundness and quality of the castings. The squeeze-casting parameters which are shown in order of importance are melt volume and quality, magnitude and duration of applied pressure, die temperature,

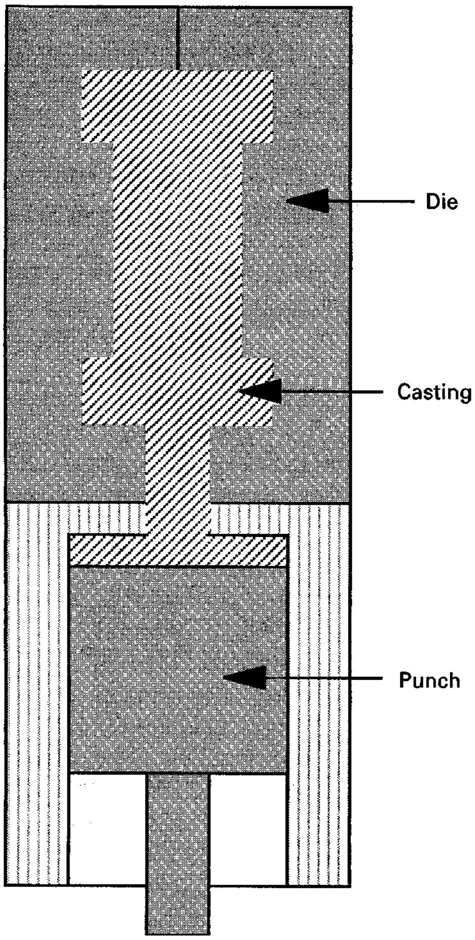

Figure 2 Schematic diagram of the indirect squeeze-casting method.

pouring temperature, time delay before pressurization and lubrication. All these parameters require to be optimized for each individual alloy system and casting.

3.1. Melt volume and quality

Owing to lack of runners and gates to accommodate any excess metal in the direct process, all the metal poured in the cavity stays in direct squeeze casting. Accurate metering of the metal volume is critical for the direct process while the die cavity is being filled. Metering of metal volume ensures that the final dimension of castings can be achieved. Lynch [53] proposed an alternative to precision control of metal volume, which is able to divert the excess metal into a non-critical region of the casting to be trimmed subsequently. In addition, for the same reason, that is, no gating system, more attention has to be paid to the melt quality, in terms of dross, in the direct than in the indirect processes. However, in both direct and indirect squeeze castings, the presence of absorbed gases in the melt is less critical than in any other casting processes, owing to the nature of squeeze casting where the imposed pressure is usually sufficiently high to suppress gas evolution and retain gases in solution.

3.2. Magnitude and duration of applied pressure

The pressure as a primary parameter in squeeze casting has the most significant effects on a component via a variety of approaches which basically include changes in solidification temperature of alloys and increases in the heat-transfer rates across the casting/mould interface. All these, in turn, affect the solidification behaviour of a casting, which consequently is manifested in the microstructure and mechanical properties of alloys.

The effect of applied pressure on the solidification temperature of an alloy is given by the well-known Claucius–Clapeyron equation

$$\frac{\mathrm{d}T}{\mathrm{d}P} = \frac{T_{\mathrm{m}}\Delta V}{H_{\mathrm{f}}} \tag{1}$$

where P is the applied pressure, T_{m} is the solidification temperature, ΔV is the voltage change during solidification, and H_{f} is the latent heat of fusion. During solidification, normally both ΔV and H_{f} are negative due to the shrinkage of metals and heat release, respectively. Thus, $\mathrm{d}T/\mathrm{d}P$ is positive, which indicates that increase in applied pressure results in higher solidification temperature. For pure magnesium, Sekhar [54], calculated $\mathrm{d}T/\mathrm{d}P$ which is about $0.0647\,^{\circ}\mathrm{C\,MPa}^{-1}$. Moreover, it has been reported in the literature [8, 55–57] that the applied pressure has an effect on the equilibrium phase diagram by shifting the liquidus and solidus lines, and even the eutectic composition. These shifts are more often toward the alloy component that is less influenced by the pressure. For the magnesium–aluminium alloy system, the eutectic point is shifted toward higher concentration of magnesium, as shown in Fig. 3.

The applied pressure also has a marked effect on heat transfer during the solidification of the castings. This is particularly true while the die is made of metal, because the die/casting interface becomes the greatest resistance to heat transfer. Owing to contraction of most metals and thermal expansion of the mould during solidification, the detachment of the casting

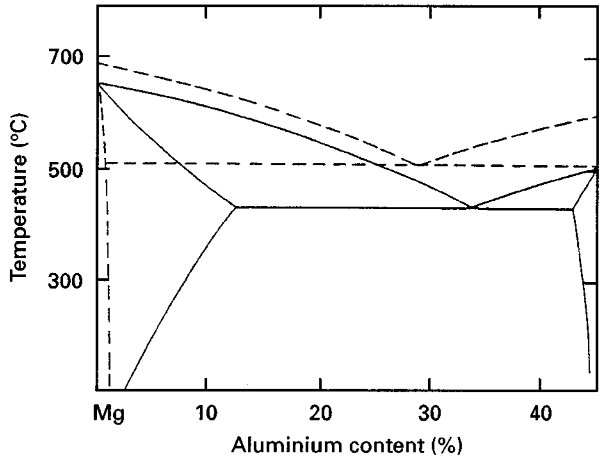

Figure 3 (– – –) Deviation from (——) equilibrium conditions in the Mg–Al phase diagram due to a rapid cooling rate resulting from a high applied pressure [55].

from the die wall takes place once the initial solid shell of the casting has sufficient strength to hold the remaining molten metal. Consequently, an air gap is formed between the die wall and casting, which considerably increases resistance to the heat transfer. In squeeze casting, the applied pressure on the casting forces the initial solid shell to remain in contact with the die for a certain period of time before any detachment could occur. If the applied pressure is sufficiently high, the intimate metal–die contact can be maintained via the plastic deformation of the casting throughout solidification. This leads to very fast heat transfer, high cooling rates and increase in casting temperature gradients. Murthy and Satyanarayan [58] found an increase in the cooling rate from 11 °C s^{-1} in permanent mould casting to 282 °C s^{-1} in squeeze casting. The study by Fujii *et al.* [59, 60] on squeeze casting of an alluminium alloy indicates that the solidification time is only a half the time in gravity castings; the heat-transfer coefficient is four times higher than that in gravity castings; and temperature gradients in the casting increase with applied pressures. Lipchin [55] reported that the solidification time of pure zinc in squeeze casting decreases with the increase in pressure levels. Few reports have been documented in the literature of the effect on the heat transfer and cooling behaviours of magnesium alloys in squeeze casting.

3.3 Tooling temperature

Operating temperatures of the die cavity and the punch are also important parameters which affect the heat-transfer rates and consequently the cooling behaviour of materials in squeeze casting. In the selection of the appropriate die and punch temperatures, a balance must be made between the requirement for sufficient heat to avert premature solidification of metals, cold laps on the surface of the casting and thermal fatigue in the tooling, and the necessity to prevent the tooling being overheated, which can cause hot spots and shrinkage pores in the casting. For ferrous squeeze casting, there is a tendency for welding between the casting and the tooling, while using very high tooling temperature. Tooling temperatures between 200 and 300 °C are appropriate in most applications. Temperatures greater than 300 °C are not recommended for aluminium alloys. Although it has been reported [51] that a lower die temperature at 150 °C can result in an equaxied grain structure for magnesium alloy AZ91D, the detailed values for magnesium alloys are still unknown. Under production conditions, a means of cooling the die by either water or oil may be employed to extract heat generated during each casting cycle.

3.4. Pouring temperature

The temperature at which the molten metal is poured into the die cavity significantly influences the casting quality and die life. The paucity of a gating system in squeeze casting manifests that a lower fluidity of molten can be tolerated, because the filling details of the die are mostly achieved by pressurization. As a result, relatively lower pouring temperatures compared with other casting processes may be used in squeeze casting. However, too low a pouring temperature could result in the insufficient fluidity, which leads to incomplete die fill and cold laps. On the other hand, too high a pouring temperature might cause extrusion of liquid metal between the interfaces of die, punch and casting, which jams the tooling. Also, shrinkage porosity might occur in thick sections of the casting. A high pouring temperature can reduce the die life significantly.

Pouring temperature for operation is dependent on several factors, such as the liquidus temperature, freezing range of the metal and die complexity. Normally, higher superheat above the liquidus is required for narrow freezing range metals due to their relatively fast solidification rates. For aluminium alloys, the casting temperature may range between 10 and 100 °C above liquidus. Superheats varying from 30–140 °C have been used in the previous study for magnesium alloys [51, 52].

3.5. Time delay before pressurization

Time delay is the duration between the actual pouring and the instant at which the pressure is applied on the molten metal via the punch. During this period a critical ratio of the solid and liquid metal in the casting is established. It has been suggested [21, 22] that optimum structures in the casting are attained as the pressure is imposed near the zero fluidity temperature of the molten metal. The zero fluidity temperature is interpreted as being reached when continuous solid-phase skeletons have formed in a two-phase alloy, and the metal loses its fluid flow properties. It is usually midway between the liquidus and solidus of the alloy. However, others [61] reported that the metal should be mainly liquid, when the pressure is applied, for squeeze casting to be effective.

The time delay changes greatly, depending on the pouring temperature, complexity of the casting and alloy systems. In general, it ranges from a few seconds for small and complex ferrous components to approximately 1 min for large and simple aluminium alloy castings. For magnesium alloys, the effect of this time delay on the properties and structures of the casting is still unknown and needs to be investigated.

3.6. Lubrication

Although the selection of die coating and parting agents often depend on the type of die materials and composition of casting alloys, it has been demonstrated [21, 22, 26] that the parting agents employed in pressure die casting can perform the same function in squeeze casting. For most non-ferrous applications, water-based colloidal graphite is a commonly used parting agent, which is sprayed on to the surfaces of the warm dies and punch prior to each casting. Owing to the applied high pressure, the influence of the coating thickness on the solidification of the casting is negligible. However, care should be taken to avoid excess buildup of the agents because the coating might be stripped from the die surface, which could cause surface contamination in the component. In general, the thickness of the coating is limited up to 50 μm.

4. Optimization of the squeeze casting process

According to the discussion made in the preceding section, the quality of squeeze-cast components is influenced by varying processing parameters, such as applied pressure, die and melt-pouring temperatures, melt quality and quantity, lubricant film thickness and its adherence. Among them, the pressure and die temperature are two primary parameters. It has been realized that the full economic and technical potential of squeeze casting can be achieved only while the process is run with the optimized parameters. Mathematical modelling as a great tool provides many benefits for process simulation and optimization, by which some primitive and time-consuming procedures in finding the appropriate set of process parameters for producing sound castings, could be avoided. Despite extensive utilization of mathematical modelling in various casting processes, published work on its application to squeeze casting is limited. Zhang and Cantor [62] reported that a heat-flow model for squeeze casting of aluminium alloys was developed. However, their model used the strong solution to account for the evolution of phase change, and failed to take into consideration a significant change in thermophysical properties with a change in phase. Recently, a mathematical model [63] has been developed at ITM to simulate heat transfer and solidification phenomena of a magnesium alloy (AZ91D) occurring in a squeeze-casting process. The model was based on the control-volume finite difference approach and on the enthalpy method. The simulations were run to determine the effect of varying processing parameters, such as applied pressure, die and melt-pouring temperatures, on solidification and cooling behaviour of AZ91D. The model predicted the temperature distributions, the shape and position of the phase front, and total solidification time of a cylindrical squeeze-cast ingot. The predictions indicate that high applied pressures and low die and melt temperatures result in high heat transfer across the ingot/die interface, and consequently solidification and cooling rates increase. In addition, it seems from the predicted results (Fig. 4) that an applied pressure of 80 MPa is high enough to maximize the solidification and cooling rates of the casting. Further increase in the pressure beyond the value of 80 MPa has a minor influence on the solidification rates of the casting. For higher die temperatures, a slight increase in the applied pressure results in a significant acceleration of the entire solidification process.

In addition to mathematical modelling, another alternative to the optimization of the squeeze-casting process is the Design of Experiments (DOE) methods, which are nowadays also extensively used for solving casting problems and for tuning up operating parameters in the casting industry. The DOE methods are powerful statistical techniques, and can improve the quality of components dramatically when used in the right situation. Little work on the application of the DOE to squeeze casting has been reported in the literature. Attempts [64] are being made at ITM to employ one of the DOE methods, the Taguchi approach, to optimize the squeeze-casting process of magnesium alloys and their composites.

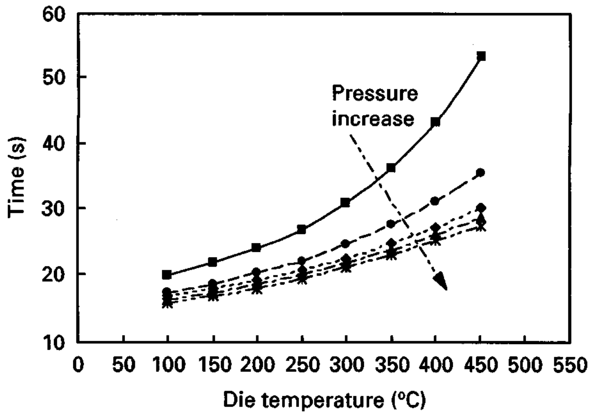

Figure 4 Effect of applied pressures and die temperatures on total solidification times at the casting centre. (■) 0 MPa, (●) 40 MPa, (◆) 80 MPa, (▲) 120 MPa, (*) 160 MPa.

5. Squeeze casting of magnesium alloys

As mentioned earlier, numerous references are available in the literature on the squeeze casting of aluminium alloys, and, more recently, the aluminium casting industry has successfully exploited the squeeze-casting process to produce various components [26, 27, 65, 66]. However, squeeze casting of magnesium and its alloys has not been so widely explored.

Over the past few years, a few papers have been published in the open literature [23, 45, 46, 51, 52] in regard to squeeze casting of magnesium alloys. Owing to the fact that AZ91 is the most common magnesium casting alloy, most of these studies are focused on this alloy. Ha [51] studied the effect of three critical parameters, i.e. the magnitude of pressure, die temperature and pouring temperature, on the solidification behaviour and resulting microstructure of two different types of magnesium alloys, designated AZ91 and AZ31. The results indicate that the pressure leads to an increase in the melting temperature of both alloys (7.58 and 8.70 °C for AZ91 and AZ31 under 115 MPa, respectively), and a significant decrease in the total solidification time. Also, it has been shown that the long freezing range alloy (AZ91) needs a higher pressure to produce a pore-free casting than a short freezing range alloy (AZ31). It was found that pore-free castings can be obtained under an applied pressure of 100 MPa for AZ91 and 50 MPa for AZ31. Low die and pouring temperatures and high pressure can result in fine grain structure in both AZ91 and AZ31 castings. The tensile properties of both the squeeze-cast AZ91 and AZ31 are higher than those which are gravity cast. Later, similar investigation [46, 52] was carried out on squeeze casting of AZ91. In that study

AZ91 was squeeze cast under an applied pressure of 138 MPa with a die temperature of 250 °C and heat treated under the T6 condition. The results indicate that the squeeze casting signficantly enhances the tensile properties of the AZ91-T6 alloy compared with the permanent mould casting, and the microstructure of the squeeze-cast AZ91 alloy is featured with fine grains. It has been suggested that longer duration of pressurization is required in order for taller castings to reduce their porosity levels. Recently, Chadwick *et al.* [23] compared the squeeze-cast AZ91 in terms of its properties with those cast by other processes, such as sand casting, gravity die casting, and high-pressure die casting, in the as-cast and in the fully heat-treated condition. Figs 5 and 6 show the variation in properties of AZ91 produced in the different conditions. In all cases, the squeeze-cast specimen exhibits the highest values of yield strength, UTS and elongation to failure. The full heat-treatment cycle enhances the UTS of the squeeze-cast specimen from 200 MPa to 260 MPa with a resulting decrease of elongation of only 1%.

The research work on squeeze casting of magnesium alloys at ITM is motivated by the development of automotive applications such as pistons and wheels. A preliminary study [67] is being carried out on squeeze casting of AZ91D alloy with a pressure of 87 MPa and a die temperature of 450 °C. It is observed that the squeeze-cast AZ91D alloy has virtually no porosity in the microstructure as shown in Fig. 7a. However, the typical pores can be easily spotted in the high-pressure die cast plate as indicated in Fig. 7b. The difference in casting soundness in terms of the porosity level between squeeze casting and die casting is quantitatively illustrated in Fig. 8 based on the density measurements. With such a low porosity level, higher elongation of the squeeze-cast specimen is expected. Mechanical properties of both the squeeze-cast and die-cast alloy AZ91D specimens are summarized in Table I. The elongation of the squeeze-cast AZ91D specimens is 5%, 10.5% and 6.5%, signifying an increase of 67%, 250%, and 117% over that of the die-cast AZ91D for as-cast, T4 and T6 conditions, respectively. Although the strengths (both YS and UTS) of the squeeze-cast specimens in the as-cast condition are lower than those of die casting, the squeeze-cast parts show slightly higher ultimate strength (255 MPa) after T6 treatment than that of die casting (230 MPa). The low yield and ultimate tensile strengths of the squeeze-cast specimens in the as-cast condition are directly attributed to their coarse grains and intermetallic particles, mainly due to the high die temperature used. Higher strengths are envisioned when the parameters of the squeeze-casting process are optimized in further investigation. In addition, it confirms that parts produced by the squeeze casting are heat-treatable compared with die cast parts, in which surface blistering usually occurs during heat treatment. Examination of the fracture surfaces of tensile specimens via SEM manifests the difference in the fracture behaviour between the squeeze-cast and die-cast parts, as shown in Fig. 9. It is evident from Fig. 9a that the failure of the die-cast specimens is caused by a combined brittle fracture mechanism of

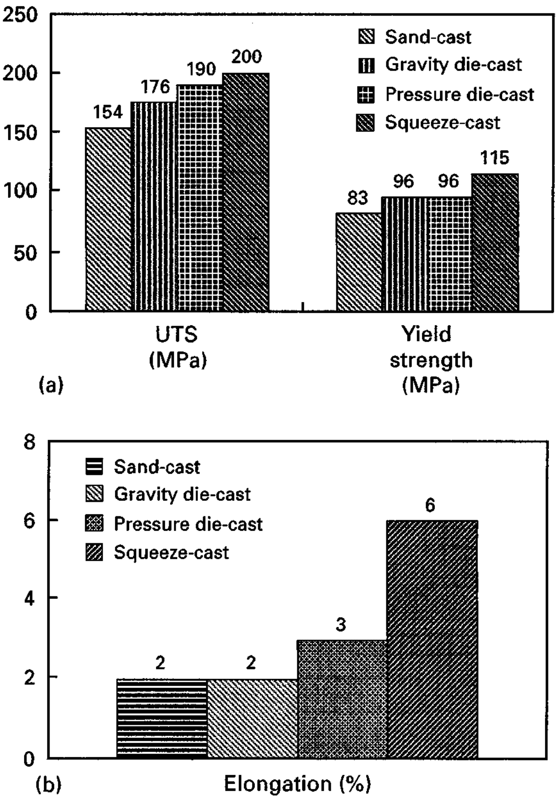

Figure 5 Mechanical properties of cast AZ91 in the as-cast condition. (a) UTS and yield strength, (b) elongation [23].

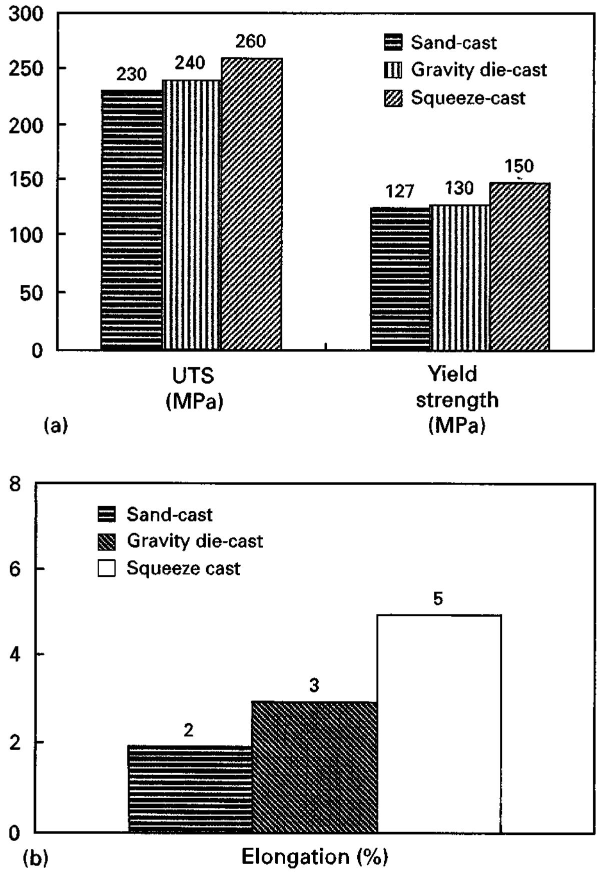

Figure 6 Mechanical properties of cast AZ91 in fully heat-treated condition. (a) UTS and yield strength, (b) elongation [23].

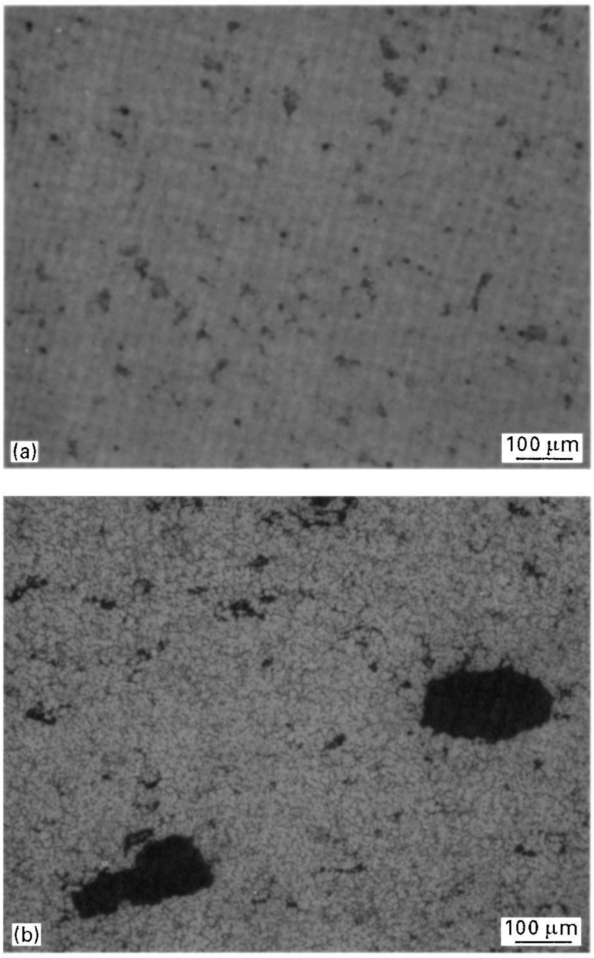

Figure 7 Optical micrographs showing microstructure of (a) a squeeze-cast part, and (b) a die-cast part in the as-cast condition.

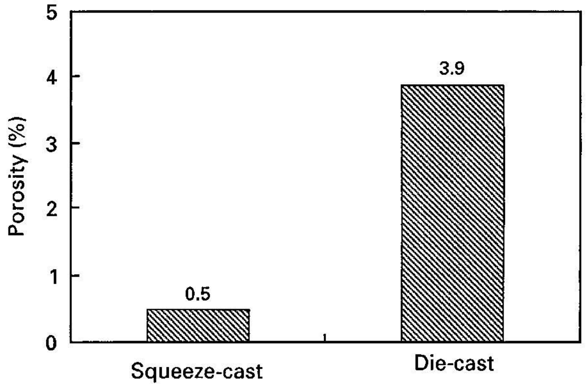

Figure 8 Porosity levels of squeeze-cast and die-cast parts.

TABLE I Tensile properties of squeeze-cast AZ91D alloy at room temperature

Casting condition		Yield strength (MPa)	UTS (MPa)	Elongation (%)
Squeze-cast	As-cast	96	179	5.0
	T4	76	220	10.5
	T6	117	255	6.5
Die-cast	(as-cast)	150	230	3.0

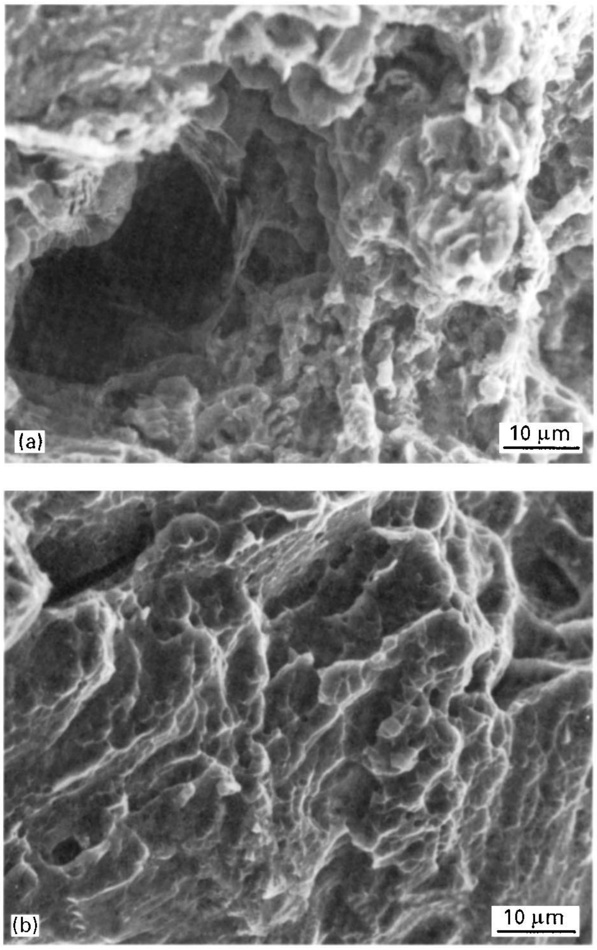

Figure 9 SEM fractographs of (a) a die-cast part, and (b) a squeeze-cast part.

void coalescence and intergranular fracture due to the presence of pores serving as the initiation point of cracks. The fracture behaviour of the squeeze-cast specimens is, however, quite different. Their fracture surfaces shown in Fig. 9b are primarily ductile in nature. The entire fracture surface of the squeeze-cast specimen is characterized by the presence of the dimples.

Owing to its inherent low strength, the improvements in properties of AZ91 achievable by squeeze casting and full heat treatment are limited to a certain extent in comparison with high-pressure die casting. Because the fluidity is not a critical parameter for squeeze castings, compositions beyond the casting specification of AZ91, which are difficult to cast with conventional casting processes, are being taken into consideration during the development of new alloys at ITM. Increases in the properties are anticipated via enhanced precipitation hardening in the porosity-free matrix with the help of the extra solute content.

6. Squeeze casting of magnesium-based composites

In recent years, reinforced magnesium composites are of great technological and commercial interest for use in aerospace and automotive applications. This is due to their high specific strength, high specific stiffness even at elevated temperatures, high damping capacity, and near-zero thermal expansion coefficient. Different types of reinforcement in various forms such as continuous fibres, discontinuous fibres, whiskers and particulates can be introduced into the magnesium matrix. Owing to economic considerations and restrictions of fabricating methods, the selection of the reinforcement is often restricted to those which are inexpensive and readily available. SiC, Al_2O_3 and graphite are most frequently used as a reinforcement being added to a magnesium matrix. Magnesium composites can be produced by several techniques, such as stir mixing, powder metallurgy process, thixocasting, preform infiltration, and squeeze casting. Among them, the most promising technique is squeeze casting plus either preform infiltration or stir mixing. This is because the porosity as the most critical microstructural feature often occurs during the production of the metal matrix composites, which is attributed to the shrinkage of metals during their solidification. Squeeze casting has a clear advantage over other processes in producing zero-porosity castings.

6.1. Stir mixing and squeeze-casting process

The stir mixing technique is usually to fabricate composites with relatively low-volume fractions of reinforcement ranging from 10%–20%. Rozak [52] integrated the stir mixing method into the squeeze-casting process to produce an AZ91 magnesium composite containing 20 vol % particulate SiC under an applied pressure of 140 MPa and with a die temperature of 230 °C. The results from his study indicate that squeeze casting produces a finer cast structure with a more uniform particulate distribution compared to the gravity-cast composites. The introduction of the SiC particulates refines the grain size and improves the properties and structure of AZ91D. For instance, an increase in specific stiffness was obtained, and the coefficient of thermal expansion (CTE) was reduced for the AZ91D alloy with the presence of the SiC particulates in the composites. However, he observed that the as-cast grain sizes of the squeeze cast AZ91D/SiC composite are similar to those gravity cast, and are independent of the volume fraction and reinforcement size. This observation implies that different grain-refining mechanisms are operating in the gravity and squeeze casting. Detailed investigation in understanding these phenomena is needed. The application of this fabrication technique to produce magnesium composites reinforced with other types of reinforcements is worth exploring.

6.2. Pressure infiltration process

In order to tailor the characteristics of a casting to specific requirements of an application, the squeeze-casting process provides the opportunity to incorporate fibre preforms into selected areas where the property enhancement is needed. The hybridization of the squeeze-casting process and the preform infiltration method, referred to as pressure infiltration techniques, is capable of fabricating composites with high-volume fractions of reinforcement (40%–50%). Owing to its merits, this technique is becoming increasingly popular in the fabrication of metal matrix composites for both laboratory research and commercial developments. Attempts were made by Ha [51], using the pressure infiltration technique with a die temperature of 260 °C, to produce AZ91 alloy-based composites in which Saffil fibre, a mixture of glass/graphite fibre and unidirectionally aligned stainless steel wire were used as a reinforcement phase. His study reveals that a complete infiltration can be achieved under a pressing pressure of 100 MPa, and the mechanical properties of AZ91, such as the hardness, fatigue strength and creep resistance at elevated temperatures are improved by the fibre reinforcement. Guldberg *et al.* [47] employed the pressure infiltration technique to manufacture Saffil Al_2O_3 fibre-reinforced AZ91 and AZ41 composites. In their study, the performs bound by colloidal SiO_2 were preheated to 800 °C; a die temperature of 250 °C and a pouring temperature of 750 °C were used, and an effective pressure of 130 MPa was applied. The evaluation of these two composites shows that tensile properties at elevated temperatures and creep resistance increase significantly with the help of the reinforcement. They also found that the thermal expansion coefficients vary considerably with regard to temperatures and volume fractions of the reinforcement for both AZ91 and AS41 matrixes. A decrease in both thermal conductivity and ductility of the composites was observed compared with the unreinforced material. With this technique, Chadwick and Bloyce [45] used hybrid preforms containing both Saffil fibres and silicon carbide particles in varying proportions to produce an AZ91-based composites. They concluded that increases in modulus of elasticity, fatigue strength, wear resistance, strength at elevated temperatures and a reduction in the thermal expansion coefficient are the benefits attained from using ceramic preform reinforcements, but penalties are also evident, i.e. decreases in ductility and toughness and a significant rise in cost. Besides SiC and Al_2O_3 reinforcements, carbon fibres have also been used as a reinforcement to produce magnesium-based composites via the pressure infiltration technique [68–70].

Despite the excellent properties of the infiltrated preform composites, the actual strength of the magnesium-based composites is still far less than the theoretically calculated values. This is due to the fact that magnesium is highly reactive with most reinforcements. Fazal-ur-Rehman *et al.* [48] examined the fibre/matrix interactions in alumina fibre-reinforced magnesium composites fabricated by the pressure infiltration technique. They found that the overall extent of reaction between matrix and fibre is influenced by the volume fraction of fibres and locally by the formation of metals channels between fibre bundles; and fibre microstructure and porosity are the key features which significantly affect the extent of chemical interactions. It is concluded from their study that increasing the aluminium content of magnesium alloys used as a matrix reduces the degree of chemical reaction between matrix and alumina fibre. They also suggested that, in order to make full use of alumina fibres, appropriate methods which are capable of stabilizing or protecting the fibres need to be developed. For infiltrated carbon fibre-reinforced magnesium composites, an attempt [69] was made to enhance the wettability between carbon fibres and magnesium by fibre treatment with compatible wetting agents. Ottinger *et al.* [70] developed another approach which improves the wettability between carbon fibres and magnesium through carbide-forming reactions between the carbon fibres and alloying elements, such as aluminium and zirconium.

Recently, Lee *et al.* [49] investigated the effect of applied pressures on the fracture process of the magnesium-based composites. Their composites were produced under pressures ranging from 35–70 MPa with a pouring temperature of 750 °C. From the *in situ* fracture tests of the Kaowool amorphous alumino-silicate fibre-reinforced composites, they observed that microcracks were initiated at the short fibre/matrix interfaces for the composite processed with the lower applied pressure, whereas microcracks were easily formed at the very low stress intensity level on short fibres which were already fractured during squeeze casting for the composite processed with the higher applied pressure. For the composites reinforced with Saffil short fibres, they found that microcracks were originated mainly at the fibre/matrix interfaces at the considerably higher stress intensity factor level, as almost no degradation of fibres was observed even in the case of the very high applied pressure. The resulting suggestion of their investigation is that the better mechanical properties of magnesium composites fabricated by squeeze casting are attributed not only to the higher applied pressure, but to the inherent fracture toughness of the reinforcement. The effect of the graphite lubricant coated on the inside of a die on the preform deformation was examined by Nakagawa *et al.* [50]. In their study, alumina short-fibre/AZ91D magnesium composites were fabricated using the pressure infiltration technique under an imposed pressure of 49 MPa with a die temperature of 350 °C, a pouring temperature of 700 °C and a preform temperature of 750 °C. They found that the preform deformation is caused by the α primary phase which crystallizes on the surface of the die. By coating the graphite lubricant on the inside of the die, the crystallization of the α primary phase was eliminated on the surface of the die. As a result, no preform deformation occurred.

Lately, an ITM/CANMET joint research team has been developing a squeeze-casting process for fabricating magnesium composites with relatively high-volume fractions of reinforcements. This technique consists of two distinct stages. The first stage involves the preform fabrication, in which an Al_2O_3 binder is used to form a rigid three-dimensional network of inter-connecting particulates. In the second stage, molten magnesium is infiltrated onto the heated preform under an applied pressure in a preheated die. An AZ91D composite reinforced with 40 vol % silicon carbide particulates was successfully produced with this technique, where a pressure of 87 MPa was employed, and the die and the preform were preheated to 450 and 650 °C, respectively. Fig. 10 is an optical micrograph showing the microstructure of the AZ91D/40 vol % SiC_p composites. It can be seen from Fig. 10 that the SiC particulates are distributed uniformly in the AZ91D matrix. Reinforcing AZ91D with SiC particulates results in a significant increase in mechanical properties. Fig. 11 compares the modulus and ultimate tensile strength of the SiC/AZ91D composite with that of the matrix. The modulus and ultimate tensile strength of the SiC/AZ91D composite are 176 GPa and 302 MPa, whereas, AZ91D offers only 45 GPa in modulus and 255 MPa in ultimate tensile strength. However, certain challenges are also encountered in the present study. Internal cracking in this type of the composites is observed, which probably results from the high applied pressure and the large difference in the thermal expansion coefficients of reinforcements and magnesium matrix. Further study on the process optimization is being carried out in attempts to eliminate the internal cracks and produce high-quality components.

7. Conclusion

Although a number of studies have been reported with regard to the application of squeeze casting to magnesium alloys, most of them are focused only on

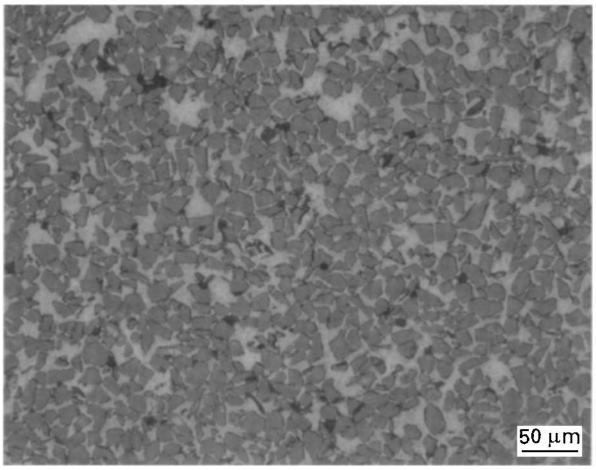

Figure 10 Microstructure of squeeze-cast AZ91D composite reinforced with 40 vol % SiC particulates.

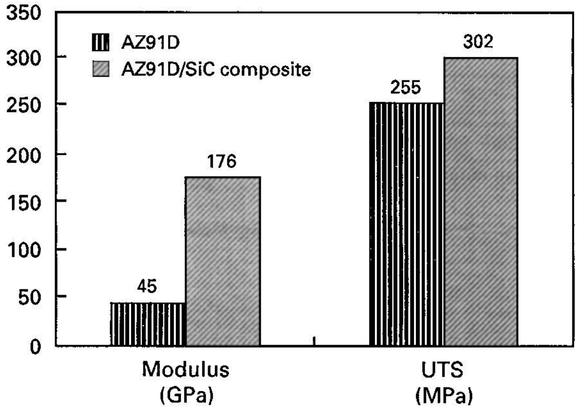

Figure 11 Mechanical properties of squeeze-cast AZ91D and AZ91D/40 vol % SiC composite.

magnesium–aluminium–zinc based alloys such AZ91 and AZ31, and their mechanical properties. No applications of squeeze-cast magnesium components have been revealed in the open literature. Also, the relationships between squeeze-casting parameters and the microstructure and properties of magnesium alloys are still unclear. Both theoretical and experimental work on the effect of applied pressure on the solidification and cooling behaviour of magnesium alloys is required. In order to optimize squeeze-casting processes, the potentials of DOE (Design of Experiment) methods and mathematical modelling should be explored. The development of new alloys should take advantage of the squeeze-casting process, for which their castability is not critical.

Compared with the squeeze-cast magnesium alloys, it appears that the development of magnesium-reinforced composites has received more attention. This is probably because the squeeze-casting process is most capable of suppressing the porosities which often occur during the fabrication of metal matrix composites, and producing composites with high-volume fractions of reinforcement or selectively reinforced composites. The most promising technique to produce magnesium-based composites is pressure infiltration, which is a hybrid of the squeeze-casting process and the preform infiltration method. Various magnesium-based composites have been fabricated with the pressure infiltration techniques, but only on a laboratory scale. It is evident that the mechanical properties of magnesium-based composites have been improved over those of the monolithic material. However, certain problems are also encountered with the pressure infiltration techniques. For instance, preform deformation occurs during composite fabrication, and internal cracks are observed in the composites. Therefore, it is essential to investigate more systematically and methodically the effect of squeeze-casting parameters, particularly the pressure level, the preform temperature and the die temperature, on the cast structure and mechanical properties.

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