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Squeeze casting for metal alloys and composites: An overview of influence of process parameters on mechanical properties and microstructure

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Abstract: Squeeze casting is a well-established and reliable process for fabricating high-integrity metallic alloys, bimetals, and composites. The quality and high performance of squeeze cast components are dependent on optimum casting conditions. Inappropriate selection of parameter values may adversely affect the quality of the casting. The squeeze cast components are generally subjected to secondary processing such as heat treatment, extrusion, and other bulk deformation processes to improve the microstructural features and mechanical properties. Heat treatment further refines the grains and reduces porosity, consequently improving tensile strength, and hardness; however, ductility decreases. This paper provides a comprehensive review on studies concerning the influence of processing parameters on porosity, density, percentage elongation, strength, hardness, wear, and fracture of squeeze casting alloys, aiming to provide sufficient information on the squeeze casting process and the effects of processing parameters on product quality.

Keywords: composites; microstructure; optimization; porosity; solidification; squeeze casting

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1 Introduction

Over the years, squeeze casting technology has progressed from small to large-scale commercial applications. It has been employed in the production of varieties of products ranging from household items to high integrity structural components. This process is suitable for small components weighing up to 30 kg. Currently, parts such as brake calipers, suspension arms, pistons, connecting rods, and automotive wheels, etc., can be produced by squeeze casting [1-3]. The squeeze casting has been successfully used to fabricate metallic alloys, bimetals and metal matrix composites (MMC) [4-9]. Squeeze casting process involves the solidification of molten metal in a preheated die under squeeze pressure. Substantial material saving, the ability to deal with a wide range of materials, and near-net-shape fabrication are the significant benefits of squeeze casting process [2, 10-12].

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The applied squeeze pressure which is less than forging pressure causes rapid solidification cooling rate due to higher heat transfer rate, reduction in gas and bubble nucleation, and reduction in solidification time which results in refine grain structure and enhanced mechanical properties of the castings [3, 13-15].

Squeeze casting method can overcome the limitation associated with other liquid metallurgy methods such as gravity casting, permanent mould casting, etc. [13,16-18]. Squeeze cast components are characterized by minimal porosity, enhanced mechanical properties, refined grain microstructure, better surface finish, good dimensional accuracy, and improved wear properties because of the impact of squeeze pressure [2, 14, 19, 20]. Some of the drawbacks associated with this technology include micro-segregation, shape and size limitation, high tooling cost and short die life span [5, 21]. Squeeze casting is also adaptable for semi-solid metal processing. Compared to conventional squeeze casting, the semi-solid squeeze cast (SSSC) components exhibit improved mechanical properties and microstructural features [22]. This improvement can be attributed to the nucleation of refined grains at the semi-solid temperature and the uniform distribution of interfacial precipitates at grain boundaries due to the squeezing pressure. Dao et al. [23]

reported that the connecting rod fabricated by SSSC exhibited higher tensile strength and ductility than the conventional squeeze casting. To further enhance the mechanical properties and microstructural features of squeeze cast components, secondary processing such as T4, T5, and T6 heat treatment and extrusion is performed on the cast components [24–26]. Squeeze cast components subjected to heat treatment followed by an artificial aging process exhibit higher performance compared to as-cast components [6, 27, 28].

The matrix alloys for squeeze casting determine the processing parameters [5], and the squeeze casting's quality depends on optimum process parameters [29–31]. Parameters such as squeeze pressure, pressurization velocity, melt/pouring temperature, die temperature and their effects on microstructure and mechanical properties of castings have been extensively investigated [32–40]. For example, Wang et al. [41] reported that the high quality of the squeeze cast aluminum alloy scroll can be obtained using the semi-solid squeeze casting process under optimal parameter values. Hence, many designs of experiment-based investigations have been conducted to determine the optimal squeeze casting process parameters [31, 42–44].

This paper presents the outcomes of important past work conducted to examine the performance of squeeze casting technology. The effects of various process parameters on mechanical properties, microstructure, and porosity when producing various parts and components from metal alloys and composites were discussed.

2 Squeeze casting process parameters used in previous studies

Squeeze casting process parameters such as squeeze pressure, squeeze velocity, pressure duration, melt/pouring temperature, die temperature, and percentage of reinforcement volume can significantly impact the quality of squeeze cast parts [31, 41, 45, 46]. For instance, Patel et al. [47] reported that squeeze pressure, die and pouring temperature significantly influenced the wear rate of squeeze cast components. Senthilkumar et al. [17] observed that squeeze pressure and die temperature had a more substantial influence on the quality of squeeze cast metal matrix composites. From Table 1, it can be inferred that the optimal range of the squeeze casting process parameter values for both aluminum and magnesium matrices include: squeeze pressure of 100–125 MPa, pouring temperature of 700–800 °C, die temperature of 130–250 °C, and pressure duration of 45–90 s.

2.1 Effect of squeezing pressure on solidification

Squeeze pressure is one of the most significant parameters of squeeze casting [43, 44]. The squeeze pressure stimulates inter-dendritic flow during solidification. As the squeeze pressure increases, the inter-dendritic pores reduce, thereby minimizing porosity [51]. Furthermore, as the melt solidifies under increased pressure, supercooling occurs, resulting in microstructure with refined and uniformly distributed grain structure [15, 48, 61]. The effects of squeeze pressure on melt solidification can be further explained using Clausius-Clapeyron equation [5]. The recast equation is expressed in Eq. (1):

$$P = P_o \exp\left(\frac{-\Delta H_f}{RT_f}\right) \tag{1}$$

where ΔH_f is the latent heat of fusion, P_o and R are constants, P is the applied pressure, and T_f is the freezing point. As the squeeze pressure increases, the solidification cooling rate increases, resulting in supercooling and grain refinement.

During the squeeze casting process, the pressure forces the melt to fill the die cavity, thereby preventing shrinkage cavities. As the pressure increases, gas and bubble nucleation becomes difficult, resulting in minimal gas porosity. However, when the squeeze pressure becomes unreasonably high, microstructural damage becomes inevitable [13, 19, 35]. Yong et al. [62] reported that squeeze pressure of 60–100 MPa is enough to reduce porosity in fiber-reinforced magnesium matrix composites. Pressure beyond 100 MPa will result in fiber clustering and damage. The squeeze pressure can also alter the rate of solidification. According to Chvorinov's rule, the total solidification time for casting is given as:

$$T_{Ts} = C_m \left(\frac{V}{A}\right)^n \tag{2}$$

where T_{Ts} is the total solidification time (min), C_m is the mould constant ($min \cdot mm^{-2}$), V is the volume of the casting (mm^3), A is the total surface area of the casting (mm^2), and n is an exponent equal to 2 [63–66].

A study to compare the total solidification time of squeeze casting with other conventional castings has been conducted. Maeng et al. [67] reported a solidification time of 60 s for gravity cast aluminum alloy billet (B390) and 14.56 s for squeeze cast, respectively. During the solidification process in gravity casting, it was discovered that an air gap due to thermal contraction was created between the melt and die wall. The air gap caused a change in heat transfer mode from conduction to radiation and convection, resulting in a decrease in heat transfer coefficient and consequently increase of solidification time. In squeeze casting, the applied pressure increases the surface contact area between the melt and the die wall, resulting in rapid heat transfer or a higher cooling rate and a shorter solidification time.

Squeeze pressure duration varies depending on the processing condition. Different pressure durations have been used for various studies, as shown in Table 1. It can be inferred that a pressure duration of 15–120 s may be adequate to produce a high-quality casting. According to the report by Zhong et al. [68], casting shape and section thickness are determinants of pressure duration. Other studies reported that pressure duration depends on the length of time the punch can travel into the melt before complete solidification [69, 70].

The grain size of alloys and composites may be impacted by squeeze pressure. As reported by Han et al [71], the grain size of magnesium alloy reduces as the squeeze pressure increases. However, excessive pressure may coarsen the grains. This finding is consistent with other studies [18, 27, 55]. Furthermore,

Table 1: Squeeze casting process parameters used for different studies

Alloy/ Composite	Processing parameters						Ref.
	Squeeze pressure (P_s, MPa)	Pressure equipment	Pouring temperature (T_p, °C)	Die temperature (T_d, °C)	Pressure duration (s)	Optimal value P_s, T_p, T_d	
LM6/10%(SiC+Al_2O_3)	0–120	100 t hydraulic press	720	120–130	60	120, 720, 130	[48]
Al-Zn-Mg-Cu	160	3,200 kN hydraulic press	660–720	250	120	–	[36]
Al-Si	0–150	150 t hydraulic press	650–750	250	30	125, 700, 250	[49]
LM24/SiC_p/CSA	100–200	40 t hydraulic press	675–715	200–300	45	–	[31]
2124 Al& 2124 Al/10SiC_p	0–120	150 t hydraulic press	715	120–130	120	100, 715, 130	[50]
AZ91-2%Ca	83–111	–	700–800	150–250	–	111, 800, 200	[51]
A356+SiC	40–120	25 t hydraulic press	800–900	80–250	20–60	120, 850, 250	[17]
Al+B_4C	0–150	–	730	350	60	–	[52]
AM50	40–120	1,500 t Buhler SC 10/150 machine	740	200–250	–	–	[53]
2024 Al (wrought)	0–70	Hydraulic press	750	250		–	[12]
LM13	0–211	100 t hydraulic press	630–780	150–300		100, 730, 200	[14]
AA2024	0–140	–	700–800	200	–	100, 750, 200	[54]
2017A	0–100	Hydraulic press	750	250	–	100, 750, 250	[55]
Al6Si0.3Mg	0–160	60 t hydraulic press	750	250	120	100, 750, 250	[24]
AA6061	0–105	30 t hydraulic press	–	200	15	–	[32]
A6061/SiC	100	Hydraulic press	800	300	–	–	[56]
A356/SiC	0–75	1,000 kN press	670	200	30	–	[19]
ZAX12405	0–120	80 t hydrostatic press	620–680	250	20–40	120, 650, 250	[45]
Al/SiC	80	600 kN hydraulic press	700	300		–	[57]
AX51	3–90	75 t vertical hydraulic press	760	300	–	–	[58]
HMMC Al alloy	95–105	–	650–800	150–250	15–20	–	[29]
Mg-Sn/HA	150	40 t hydraulic press	820	300	60	–	[59]
Al/Al_2O_3	100	–	700	250	45		[60]

CSA = Coconut shell ash, HA = hydroxyapatite

Masoumi [58], and Raji et al. [49] suggested that the effectiveness of squeeze pressure may depend on the aspect ratio of the casting geometry. However, more information is needed to verify this claim as limited study exists in this area.

2.2 Effects of pouring and die temperatures on solidification

Optimal pouring and die temperatures conduce to high-quality castings [72]. It is therefore essential to select appropriate pouring and die temperatures to avoid casting defects. Too low pouring and die temperatures will cause:

(i) Low fluidity or high viscosity of the melt, which makes it very difficult for dies with narrow cavities to be filled [51].

(ii) Early solidification, especially for alloys with a short freezing range. Thereby making squeezing difficult, resulting in coarse grain structure [69, 73].

The high pouring and die temperatures will cause:

(i) Shrinkage and gas porosity. Increased pouring temperature increases gas nucleation in the melt thereby creating more gaseous holes [54].

(ii) Increase of thermal stress and hot crack. Increased temperature causes thermal expansion and contraction in dies resulting in cracks and shortened the die life [54].

In deciding the right pouring temperature for squeeze casting, two key factors should be considered: the melting temperature (T_m) of matrix and the solidification range [13, 74, 75]. The solidification range of melt is the gap between the liquidus and the solidus. The solidification range could be short or long depending on the alloy; this is why superheat (T_s) is required. Previous studies recommended T_s to be 10–100 °C for aluminum and magnesium alloys and 30–150 °C for copper alloys and steels. The lower limit of superheat is applied to alloys with a long solidification range, while the upper limit is applied to alloys with a short solidification range [75].

2.3 Effects of processing parameters on density and porosity

Low density and high porosity are characteristics of conventional castings [18]. These two metallurgical features are inversely related, low porosity results in high density. Porosity in squeeze casting is a defect that can adversely affect the mechanical properties of casting. It is caused by shrinkage cavities, gas holes, or high-volume ceramic reinforcement [39, 54, 76]. Squeeze casting parameters such as squeeze pressure, pouring temperature, and ceramic reinforcement volume can impact density. The applied pressure increases the compactness of the melt, thereby reducing micropores in the microstructure [39]. High temperature speeds up the rate of metallic particle diffusion to fill pore spaces. However, extreme high temperature results in gas holes in the microstructure [54]. The simultaneous application of optimal squeeze pressure and pouring temperature reduces micropores in the microstructure and increases the density of the casting.

Ceramic reinforcements are porous, therefore, high volume ceramic reinforcement increases porosity in squeeze cast composites. Raji and Khan [49] discovered that the highest density value of Al-8%Si alloys can be obtained at an optimal pouring temperature of 700 °C and a squeeze pressure of 125 MPa. In a similar study, Jahangiri et al. [54] reported that almost no micropores were discovered in the squeeze cast aluminum alloy at a pouring temperature of 750 °C and a squeeze pressure of 100 MPa [21, 77]. Maleki et al. [14] reported a maximum density value of aluminum alloy (LM13) at a squeeze pressure of 115 MPa, a pouring temperature of 730 °C, and a die temperature of 200 °C. An increase in pressure beyond 115 MPa had no significant effect on the density. In another important study to investigate the effect of porosity on the coefficient of thermal expansion, Dong et al. [19] observed that increasing squeeze pressure decreases porosity, increasing the coefficient of thermal expansion (CTE) of the A356/SiC composite. Suggesting that porous alloys and composites have low CTE and, as a result, have higher resistance to thermally induced stress [39, 78, 79].

Mathematically, the porosity (ϕ) of squeeze cast parts can be determined using Eq. (3):

$$\phi = 1 - \rho_E/\rho_{th} \tag{3}$$

where ρ_E is the experimental density of the squeeze cast part, ρ_{th} is the theoretical density [76]. For composites, theoretical density can be determined using the rule of mixtures as given in Eq. (4):

$$\rho_{th} = \rho_m v_m + \rho_r v_r \tag{4}$$

where ρ_m is the density of matrix, v_m is the volume fraction of matrix, ρ_r is the density of reinforcement, and v_r is the volume fraction of reinforcements [18].

2.4 Effects of processing parameters on microstructure

The microstructure of the squeeze cast component influences its physical and mechanical properties, and therefore determines the application of the alloy. Microstructural features such as grain size, shape, distribution and orientation can be modified during fabrication to produce components with more improved mechanical properties (tensile and yield strength, elongation, and hardness). In the squeeze casting process, application of squeeze and holding pressure results in a stronger interfacial bond between the matrix and reinforcement. Most importantly, the squeeze pressure facilitates a rapid solidification cooling rate which results in a refined and homogeneous grain structure, and consequently improves the mechanical properties [80–86]. As illustrated in Fig. 1, increasing the squeeze pressure decreases the dendrite arm spacing and grain size of the A356 aluminum alloy. The grains shown in Fig. 1(d) are more refined and homogeneously distributed than those in Figs. 1(a)–(c) due to the impact of higher pressure. The squeeze pressure can also increase the particle-to-particle surface contact area, thereby reducing pore spaces in the microstructure.

Dendrite arm spacing is one of the essential features for determining the microstructural characteristics of casting alloys. Murthy et al. [87] discovered that the rapid cooling rate of the mould was responsible for the refinement of grains and secondary dendrite arm spacing (DAS), resulting in improved mechanical properties of the cast aluminum alloy. Cruz et al. [88] observed that the strength and percentage elongation of the Al-Sn and Al-Si alloys increased as the dendrite arm spacing decreased. Similarly, Zhang et al. [89] reported a decrease in the tensile strength and ductility of cast A356 alloy as the secondary dendrite arm spacing increased. The rapid cooling rate decreases the dendrite arm spacing, resulting in refined and evenly distributed grains. The relationship between secondary dendrite arm spacing (SDAS) and cooling rate can be explained mathematically using the classic solidification theory expressed by Eq. (5) [90, 91]:

$$\mathrm{SDAS} = B(CR)^{-\beta} \tag{5}$$

where CR is the cooling rate, and B and β are constants to be determined.

Several studies have reported a reduction in SDAS as squeeze pressure increases, which agrees well with Eq. (5) [50, 51, 92]. However, this is contrary to the findings of Han et al. [71], which reported an increase in SDAS as pressure increased. Han et al. [71] reported two categories of cooling solidification rates for the squeeze cast AZ91D magnesium alloy: average cooling rate of solidification and the cooling rate at which the primary phase grows with the maximum rate. As the squeeze pressure increases, the average cooling rate of solidification increases while the cooling rate at which the primary phase grows with the maximum rate decreases, the SDAS increases. Whereas in other studies, as the squeeze pressure increases, the average cooling rate of solidification increases, resulting in a decrease in SDAS. More investigations are required to substantiate this finding.

The micrographs of squeeze cast and stir (gravity) cast aluminum composites are shown in Fig. 2. It can be seen that compared to Figs. 2(b, d), the microstructural features (grain size, boundary, distribution) of Figs. 2(a and c) are more improved due to the effect of squeeze pressure [93]. Increasing the squeeze pressure increases the cooling rate, resulting in the nucleation of more refined grains and decrease of dendrite arm spacing. Furthermore, the absence of applied pressure in the stir casting of Figs. 2(b, d) decreases the cooling rate, resulting in an extended dendrite arm spacing at the grain boundary. Figure 2 also reveals

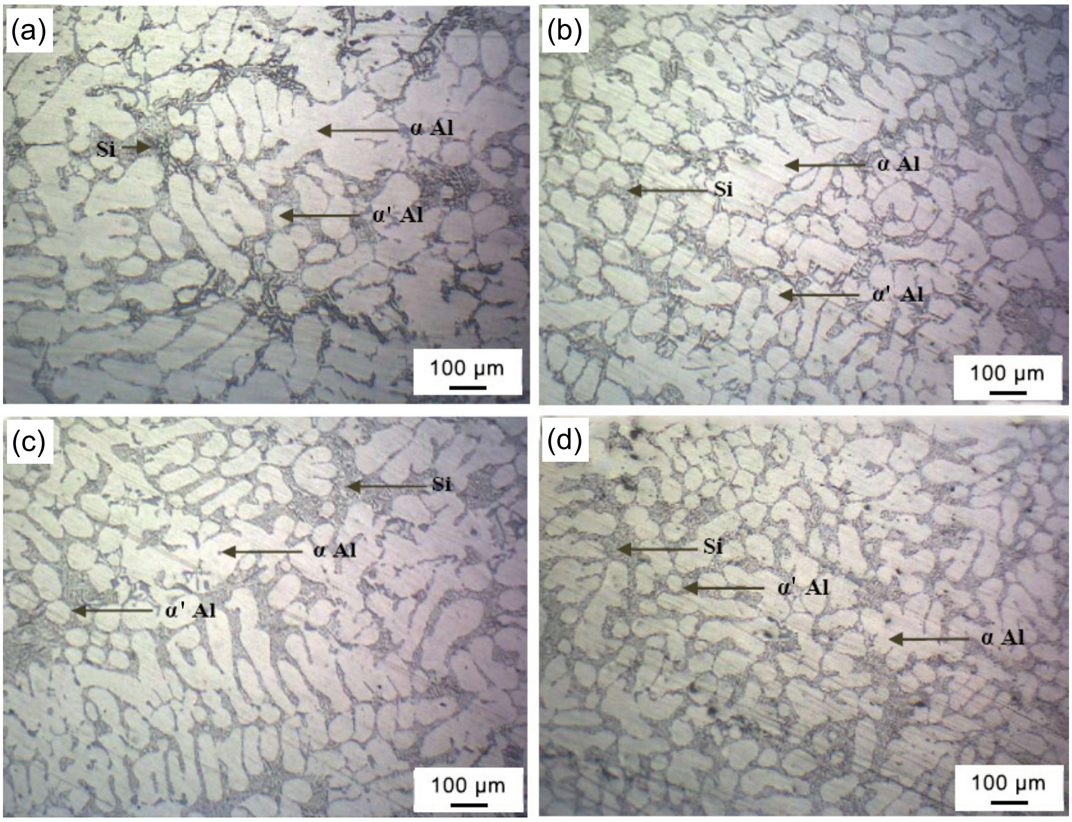

Fig. 1: Micrograph of squeeze cast aluminum alloy (A356) with squeeze pressure of 2.5 MPa (a), 3 MPa (b), 3.5 MPa (c), and 4 MPa (d) [86]

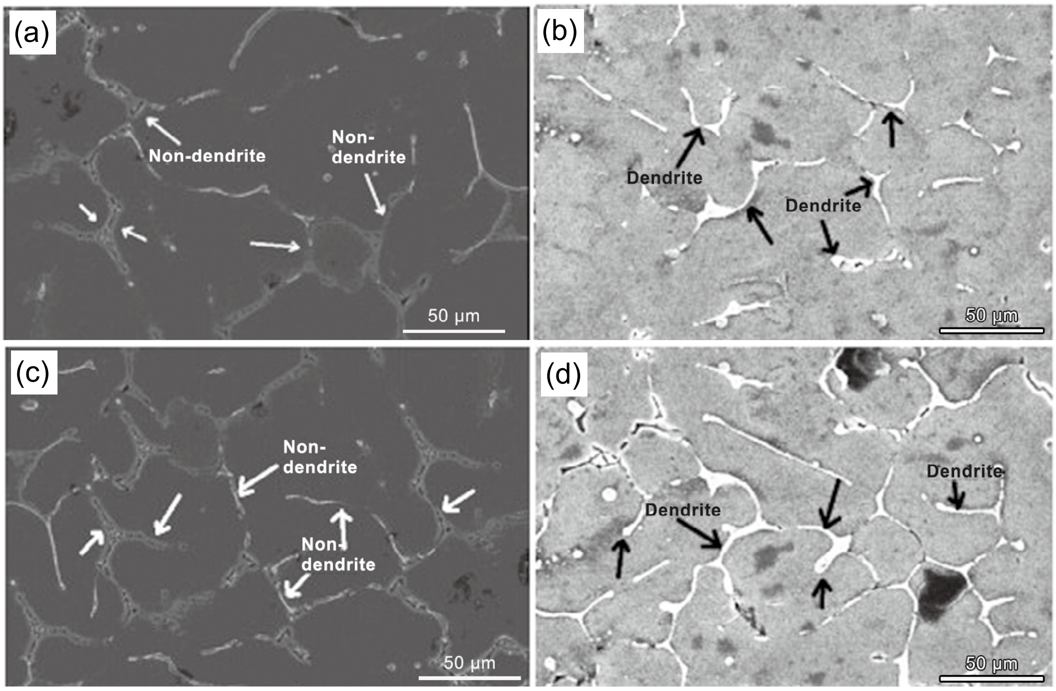

Fig. 2: SEM micrograph of Al6061 reinforced with 1wt.% (a, b), 3wt.% (c, d) nano Al_2O_3 by ultrasonic assisted squeeze casting (a, c) and stir casting (b, d) [94]

that the nano alumina (Al_2O_3) reinforcement is homogenously distributed over the aluminum matrix in both the squeeze casting composites and the stir casting composites due to the efficiency of the mechanical stirrer [84, 94].

In squeeze casting, interfacial compound formation/precipitations are likely due to interfacial reaction in the microstructure, as shown in Fig. 3. Such precipitations may have positive or adverse effects. Some precipitations distribute in the grains and grain boundaries, enhancing grain structure and impeding dislocation motion [Fig. 3(a)]. While some result in particle segregation that can degrade the microstructure and weaken the mechanical properties [Fig. 3(b)]. As reported in literature, undesirable precipitations can be prevented either by coating the secondary phase with element such as copper powder or by rapidly applying the squeeze pressure on the melt so as to increase the solidification rate and decrease interfacial reaction time [95-98].

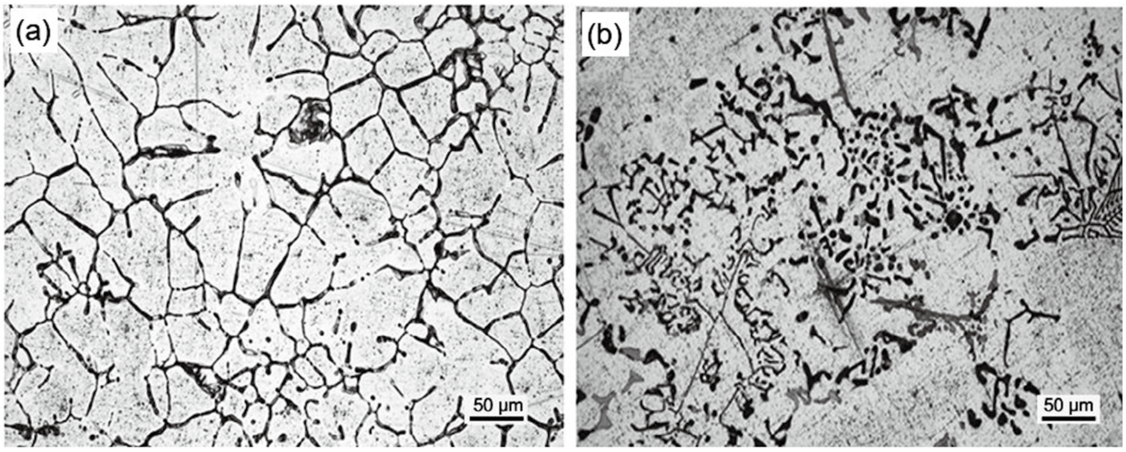

Fig. 3: Microstructures of aluminum 6061 alloy wheel spoke at zones without (a) and with (b) segregation [98]

2.5 Effects of squeeze casting parameters on mechanical properties

2.5.1 Strength and ductility

The higher strength and ductility of squeeze cast components can be achieved through an appropriate selection of optimal parameters (i.e., pressure and temperature) and the homogeneous distribution of the reinforcing/alloying particles over the matrix. More so, heat treatment can also impact on the strength and ductility of squeeze cast components [83, 99, 100]. The particle segregation results in defective microstructure, which decreases the strength and percentage elongation of squeeze cast components. Meng et al. [98] reported that the particle segregation at the R-joint of squeeze cast aluminum 6061 alloy wheel spokes was due to the slow solidification rate. Suggesting that the applied squeeze pressure was not high enough at the R-joint, thereby making the heat transfer rate very slow at that point. Increasing the squeeze pressure will cause a rapid solidification cooling rate resulting in a decrease in the interfacial reaction time, preventing unwanted precipitations and particle segregation. Christy et al. [60] reported that the best value of the tensile strength of aluminum matrix composites was a result of the effect of optimal process parameters such as a suitable squeeze pressure, pressurizing velocity, pouring temperature, die temperature, and the efficiency of the mechanical stirrer (suitable stirring speed and time). In another study, Zhu et al. [84] reported that the optimal mechanical properties (strength, ductility, and modulus of elasticity) of aluminum 6082 matrix composites reinforced with SiC_p and fabricated via squeeze casting can be obtained when the SiC_p percentage concentration was 2wt.%. Further increase of SiC_p percentage resulted in a decrease in mechanical properties. This is because increasing the percentage of ceramic reinforcement increases porosity due to the porous nature of ceramic materials, and porosity increases brittleness in metallic alloys and composites. It has been reported that the reinforcement weight percentage should be no more than 10wt.% to obtain the optimal strength and ductility of metal matrix composites [56, 58, 101, 102]. Fan et al. [93] reported the tensile strength of aluminum alloy (Al-Zn-Mg-Cu) increases as the squeeze pressure increases. Comparison between the gravity casting and squeeze casting aluminum alloy showed that gravity cast aluminum alloy exhibited lower strength than squeeze cast aluminum alloy [84,103]. The higher strength of the squeeze cast aluminum alloy is caused by the pressurized solidification, which reduces gas and shrinkage porosity. Wang et al. [104] and Souissi et al. [55] reported a maximum increase in the strength and ductility of Mg-xY-6xZn magnesium (where x=0.5%, 0.7% and 1.0%) and 2017A aluminum alloys at a squeeze pressure of 100 MPa, suggesting that the squeeze pressure of 100 MPa is optimal or most suitable in preventing grain clustering, damage and coarse grain nucleation in contrast to a very high pressure [48, 50, 105].

As illustrated in Fig. 4, the highest value of the tensile strength and percentage elongation of the 2A50 aluminum alloy scrolls after T6 heat treatment are at a squeeze pressure of 100 MPa, and casting temperature of 600 °C. Increasing the squeeze pressure beyond 100 MPa decreases the strength and percentage elongation. Moreover, the microstructural examination of the aluminum alloy scroll revealed that the best strength and percentage elongation values were obtained when the grains were well refined and uniformly distributed. Furthermore, it was also reported that the tensile strength and

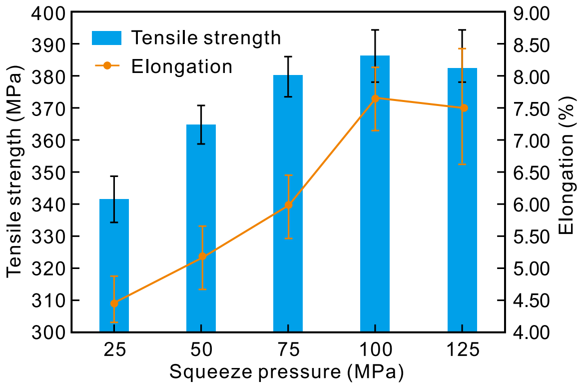

Fig. 4: Effects of squeeze pressure on tensile strength and elongation of 2A50 aluminum alloy scrolls casting at 600 °C [106]

yield strength of the semi-solid squeeze cast wrought aluminum alloy scroll improved from 286±7 MPa to 386±8 MPa after the T6 heat treatment; however, the ductility decreased from 12.3%±0.4% to 7.6%±0.5% [106].

2.5.2 Hardness

Alloys and composites have to be harder for use in cutting tool production and other wear resistant applications. Generally, the hardness of materials can be increased through reinforcement with hard ceramic materials such as SiC, Al_2O_3, TiB_2, etc., and alloying and heat treatment. In squeeze casting, homogeneous distribution of reinforcing or alloying particles over the matrix with optimal processing parameters can increase hardness [34, 49, 107, 108]. For example, the maximum hardness value of squeeze cast Mg/B_4C composite was achieved at squeeze pressure of 120 MPa, die temperature of 200 °C, and pouring temperature of 800 °C [109]. In another study by Senthil et al. [110], it was discovered that the hardness of A356/Al_2O_3/SiC/Gr composites varies due to the variation of the reinforcement volume percentage. The best value of hardness was obtained when the reinforcement volume was 3wt.% Al_2O_3/3wt.% SiC/3wt.% Gr. Further increase in reinforcement volume percentage resulted in a decrease in hardness.

As illustrated in Fig. 5, the highest hardness value of the Al-6.7% Cu aluminum alloy was at a pouring temperature of 710 °C and squeeze pressure of 7.5 MPa. Simultaneous application of optimal squeeze pressure and pouring temperature refined the grain structure and promoted a stronger interfacial bond between the matrix and the alloying particles, resulting in increased hardness. Extreme high temperature results in coarse grain structure and excessive pressure causes particle damage, leading to reduced hardness [111]. Studies revealed that the addition of Sn to Mg/HA composites and the increase of Si concentration in Al-Si-Cu alloy resulted in an increased hardness [59, 112]. A key consideration for improved hardness is the homogeneous distribution of the alloying and reinforcing phases in the matrix.

The porosity in squeeze cast parts decreases hardness. Ceramic reinforcements are inherently porous; therefore, increasing the reinforcement volume percentage of ceramic in metal matrix composites increases porosity, thereby decreasing hardness. Furthermore, particle segregation in the microstructure

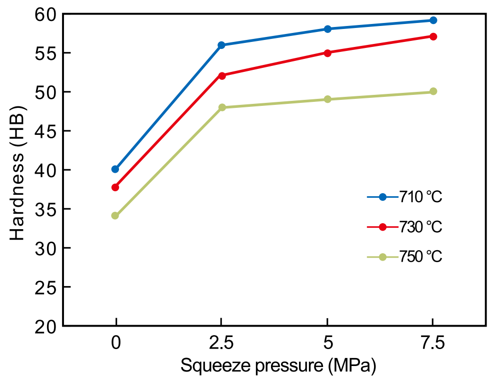

Fig. 5: Effect of squeeze pressure and pouring temperature on the hardness of aluminum alloy [111]

becomes inevitable at high volume percentage of reinforcement, also resulting in decreased hardness [76, 110, 113, 114].

2.5.3 Wear

The rate of wear is dependent on the type of material, sliding velocity, distance and wear load [115]. The wear resistance of alloys and composites fabricated through squeeze casting is higher than gravity casting [40, 107]. This may be due to the squeeze pressure which promotes a stronger interfacial bond, decreases pore size and micro-cracks. Furthermore, the wear resistance of metal matrix composites is higher than the matrix alloy due to the reinforcements, namely, fly ash, SiC, Al_2O_3 to the matrix alloy in a controlled amount [56, 116]. Figure 6(a) [117] shows the micrograph of the worn surfaces of an A390 aluminum alloy fabricated via gravity die casting. The wear mechanism is peeling delamination, a phenomenon associated with parts having softer surfaces. Figures 6(b, c) [117] show the SEM micrographs of worn surfaces of aluminum matrix composites Al/(1, 4)wt.% SiC/1wt.% Gr/1wt.% MoS_2 fabricated via squeeze casting. The addition of SiC, Gr, and MoS_2 reinforcements to the aluminum alloy matrix enhanced the tribological properties resulting in higher wear resistance [29]. The dominant wear mechanism for the squeeze cast aluminum composites with mixed layer surfaces, as shown in Figs. 6(b, c), is abrasive wear [50].

2.5.4 Fracture

Fracture modes include ductile, brittle or mixed. Generally, pure metals are ductile fracture, having facture surfaces characterized by dimple colonies of refined grains [55]. As the percentage volume fraction of the primary phase decreases, the ductility decreases, indicating the increase in porosity and brittleness. Increasing the squeeze pressure increases the compactness of the melt, resulting in increased ductility of the squeeze casting alloys [58, 118]. Figure 7 shows the SEM fractography of hybrid reinforced aluminum composite Al/SiC/Gr/MoS_2 fabricated via squeeze casting. The presence of elongated small dimples of refined grains, micropores, and tear ridges in Fig. 7(a) indicates that the aluminum-based composite absorbed some degree of energy before fracture. It also shows the ductile-brittle mixed fracture behavior. Furthermore, Fig. 7(b) shows features of cleavages, micro-cracks, a small number of dimple colonies of coarse grains, and pores, indicating also a ductile-brittle fracture. This may be due to the different concentration

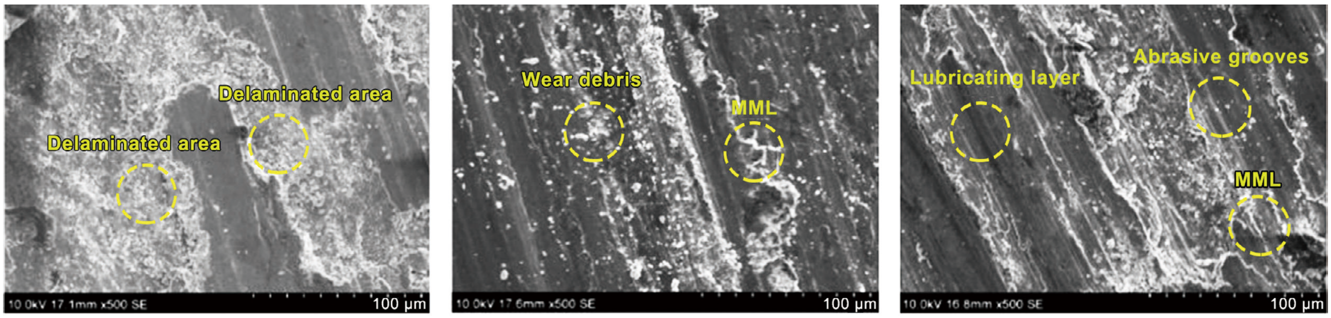

Fig. 6: SEM micrographs of the worn surface of die casting A390 aluminum alloy (a), squeeze casting Al/4wt.% SiC/1wt.% Gr/1wt.% MoS_2 (b), and squeeze casting Al/1wt.% SiC/1wt.% Gr/1wt.% MoS_2 (c) [117]

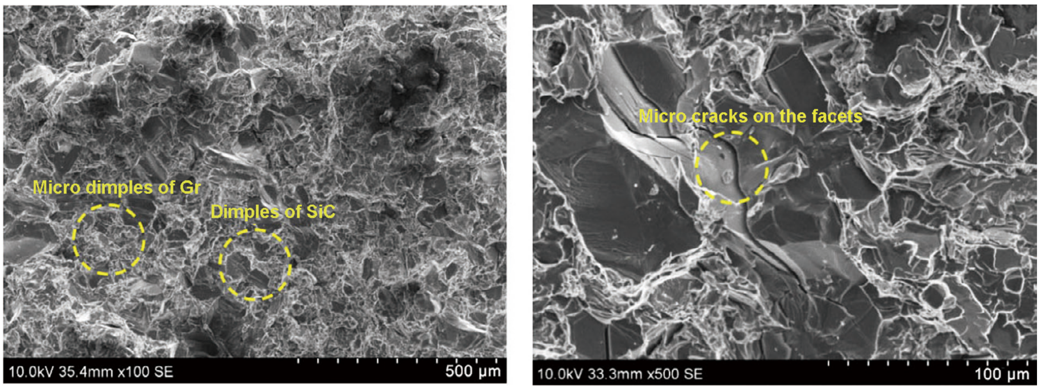

Fig. 7: SEM fractography of hybrid aluminum matrix composites Al/SiC/Gr/MoS_2 [117]

of SiC, Gr, and MoS_2 reinforcements in the aluminum alloy matrix which resulted in the different degrees of porosity and brittleness [119].

3 Summary

This paper presented a review of past works on the squeeze casting of metals and composites with special focus on the effect of process parameters on mechanical properties and microstructure of the cast parts. It is concluded that the squeeze casting is a mature process and can be used for the production of many alloys and composites. These squeeze cast products are characterized by very little or no porosity, high density, good microstructural features, and mechanical properties. Aluminum and magnesium alloys are the two most widely used metallic alloys for squeeze casting. Squeeze pressure, pressurization velocity and dwell time, pouring temperature, die temperature, superheat, and reinforcement percentage are found the most influential parameters in squeeze casting. The matrix material is also an important factor that needs to be considered to confirm the process parameters. For both aluminum and magnesium alloys, optimal parameters are squeeze pressure of 100–125 MPa, pouring temperature of 700–800 °C, die temperature of 130–250 °C, and pressure duration of 45–90 s. Future research is required to investigate the solidification temperature range of alloys and composites to determine the right superheat for casting. The knowledge of superheating will help prevent premature solidification and overly protracted solidification time which both have undesirable effects on squeeze cast parts. Furthermore, the effectiveness of squeeze pressure is somewhat dependent on the aspect ratio of cast geometry, more future investigations are required to establish this finding.

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