Extruded microstructure of Zn–5 wt-%Al eutectic alloy processed by twin screw extrusion

S. Ji* and Z. Fan

Semisolid extrusion with twin screw extruder has been successfully developed for eutectic alloy. In this process, the eutectic melt is sheared and cooled down inside the twin screw extruder to a semisolid state and simultaneously extruded through an open die at a temperature close to solidus. The accurate control of heat balance in the extruder results in the formation of two solid phases and one liquid phase in the Zn–5 wt-%Al eutectic alloy. A little plastic deformation in the extruded alloy can be introduced by twin screw extrusion. In semisolid extrusion, the particle size in Zn–5 wt-%Al eutectic alloy is close to 40 μm for Zn rich particles and 25 μm for Al rich particles. Two solid particles are at the similar size in longitudinal and transverse directions and distribute uniformly and independently on the whole cross-section of the extruded bar. The remnant liquid can act as lubricant for reducing extrusion force during extrusion and solidify in lamellar morphology between Al rich and Zn rich particles.

Keywords: Extrusion, Eutectic alloy, Semisolid metals, Solidification, Microstructure

Introduction

Conventional extrusion is a plastic deformation process that squeezes metal below its solidus temperature through an open die orifice under controlled conditions.[1] The processing temperature of metal can be at room temperature or at slightly elevated temperatures for cold extrusion and/or at fairly high temperatures of 50–75% of the melting point for hot extrusion. The high equipment costs and energy consumption in conventional extrusion are essential to overcome the friction of plastic deformation and to provide the necessary extrusion ratio. The non-uniform deformation and temperature distribution in the billet often cause quality problems in the extruded products. This is particularly severe for the conventional extrusion process when extruding the alloys with worse plasticity because surface cracking and other defects occur at the optimised extrusion speed.

Semisolid metal processing is an emerging technique to process alloy in a solid–liquid coexisting state, where the material exhibits unique and controllable thixotropic and pseudoplastic properties as a result of the globular solid particles in the liquid.[2,3] Semisolid metal processing offers a number of advantages for the production of metallic components with high integrity due to the unique processibility of the semisolid slurry. Generally, two approaches are used in semisolid metal processing,[4] which are either reheating specially made billets (thixo route) or shearing alloys at a temperature between solidus and liquidus (rheo route). The basic principle of semisolid processing has been utilised in extrusion technology to overcome the shortcomings of the conventional extrusion process.[5] Thixo extrusion and rheo extrusion have been investigated with a variety of alloys.[6,7]

In thixo extrusion, a billet is heated up to a temperature above the solidus temperature of the alloy before introducing it into a cylinder piston mechanism for extrusion. Zhang *et al.*[8] investigated the extrusion behaviour of Zn–20Al alloy in a semisolid state. They found that the appropriate operation for semisolid extrusion of Zn–20A1 alloy in temperature range from 400 to 420°C. A lower temperature resulted in cracking, while a higher temperature resulted in liquid segregation. The force required for semisolid extrusion was only half of that required for hot extrusion in the solid state. Zu and Luo[9] studied the semisolid extrusion of SiCp/2014Al composite and confirmed that only one-third to one-fifth of the extrusion forces were required in comparison to that required for fully solid extrusion. The mechanical properties of SiCp/2014Al composites that have been made by semisolid extrusion are also substantially improved, increasing the yield strength by 66–131 MPa, the ultimate tensile strength by 43–87 MPa and the modulus by 18·3–36 MPa while maintaining elongation at 3·8–8·4%. Uetani *et al.*[10] studied the semisolid extrusion of Al–10Mg alloy using a simple mechanical stirring treatment during casting. They found that the non-dendritic microstructure in the billet provided improved ductility and less surface cracking for the extruded products. Sugiyama *et al.*[11] investigated the

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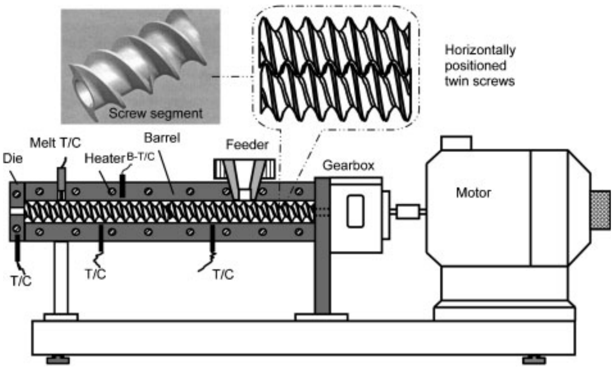
extrusion characteristics of AZ61A wrought magnesium alloy and claimed that high quality products could be made by semisolid extrusion. They concluded, however, that the extrusion speed has to be carefully controlled to avoid the formation of surface defects in the extruded products.

In rheo extrusion, semisolid slurry is made and simultaneously transferred into an extrusion machine. Guan *et al.*[12] developed a process to make AZ31 alloy wire using continuous semisolid extrusion. They found that non-uniform microstructures can be formed in the roll–shoe gap during extrusion when using a high processing temperature and fast cooling rate region near the roll surface. The appropriate parameters for semisolid extrusion are processing temperature ranges at 730–750°C, roll cooling intensity of 0·4 L s^{-1} and a roll–shoe gap width of <10 mm. The extruded 10 mm bar, after aging at 220°C for 24 h, reaches 270 MPa tensile strength and 16% elongation. Rattanochaikul *et al.*[13,14] studied the rheo extrusion of A356 aluminium alloys using a gas induced semisolid process. They found that the higher solid fraction in the slurry reduced the surface defects in the extruded parts. The non-uniform eutectic microstructure still existed; however, it was improved by enhancing the cooling along the die. Fan *et al.*[15] and Roberts *et al.*[16] developed a rheo extrusion process using a twin screw extruder. The extrusion of an Sn–15Pb alloy and an AZ91D alloy was demonstrated on a laboratory scale. The extruded alloys showed a uniform distribution of the primary phase in the matrix, and no apparent segregation was found in the products extruded under optimised conditions.

Currently, almost all of the alloys processed in semisolid extrusion have off eutectic compositions, which solidify in a temperature range from liquidus to solidus, and the resultant microstructure is characterised by one type of globular primary particles distributed within the matrix. It is well known that an alloy at its eutectic composition solidifies at a constant temperature, and the resultant microstructure exhibits lamellar morphology in conventional solidification. Therefore, it is difficult to reheat a billet with eutectic composition to a semisolid state due to the lack of temperature range of melting. However, Ji and Fan[17] have found that shearing a eutectic alloy is capable of creating semisolid slurry with a globular microstructure after processing within a twin screw extruder because the solidification process can be altered from the initial stages. The extruder can control the slurry formation, turning it from a temperature dominant process into a temperature and time dominant process.[17,18] Thus, the unique microstructure of a eutectic alloy processed by a twin screw extruder can be further developed for semisolid extrusion by increasing the volume fraction of the solid phases and introducing plastic deformation during the extrusion process. As a result, semisolid extrusion can then be applied to an alloy with a eutectic composition.

Therefore, the present paper aims to introduce the microstructure and the semisolid extrusion behaviour of an Zn–5 wt-%Al eutectic alloy. The microstructure of the solid phases in the longitudinal and transverse sections, the microstructure of remnant liquid in the extruded alloy and the torque of the screw rotation using different conditions are investigated. The discussions are focused on the thermomechanical behaviour of the materials during shear in the twin screw extruder and the microstructural evolution during processing.



1 Schematic diagram of twin screw extruder used for semisolid extrusion of eutectic Zn–Al alloy

Experimental

A ϕ16 mm twin screw extruder that is used for semisolid extrusion is schematically illustrated in Fig. 1. The extruder includes a feeder, a barrel, a pair of closely intermeshing, self-wiping and corotating screws, an open die attached at the end of extruder and a control unit. The screw has a specially designed profile and the matched heating elements and cooling channels that are dispersed along the barrel to ensure the desired temperature distribution. The shear rate used in the present paper referred to that between the inner surface of the barrel and the tip of the screw flight and was calculated by the equation $\dot{\gamma}=\pi\omega(D/\delta-2)$, where ω is the rotation speed of the screw, D is the outer diameter of the screw and δ is the gap between the tip of the screw flight and the inner surface of the barrel. There were seven thermocouples on the twin screw extruders. Four of them were for heating/cooling control; the others were for temperature measurement on the extrusion die, the barrel and the melt inside the barrel respectively. The barrel length was 50 cm, on which the measuring thermocouple for the melt temperature (denoted as Melt T/C in Fig. 1) was in touch with the melt through the barrel, but that for the barrel temperature (denoted as B-T/C in Fig. 1) was mounted close to the inner surface of the barrel. The shearing time in the extruder depended on the rotating speed, which could be varied from several seconds to a few minutes. In the experiments, the common shearing time was 60 s unless specified in the specially defined conditions.

Zn–5 wt-%Al eutectic alloy was made from pure elemental raw materials. Zn (99·95 wt-% purity) and Al (99·995 wt-% purity) were weighed and melted in an electric heated furnace. A graphite crucible was heated up to 700°C, within which Al was loaded and melted first, and then Zn was added into the Al melt in the crucible while the temperature of the furnace was reduced. The alloy was held above the liquidus temperature for at least 30 min before pouring into a metal mould to make ingots to complete the melting and ensure solute homogenisation. The alloy was analysed by optical mass spectroscopy, and its composition was determined by the average value of five points on the cross-section of the ϕ40 mm ingot. The alloy composition was adjusted in the furnace until the measured value was within Zn–5±0·02 wt-%Al. Meanwhile, one ingot

2 Representative sample of extruded Zn–5 wt-%Al alloy for microstructural examination: diameter of extruded round bar is 4·0 mm

was metallographically examined in order to observe the resulting microstructures and to confirm the homogeneity of the alloy. The ingots were remelted in an electric heated furnace that was set at 50°C above its liquidus temperature. The melt was held for ~20 min in the furnace before extrusion.

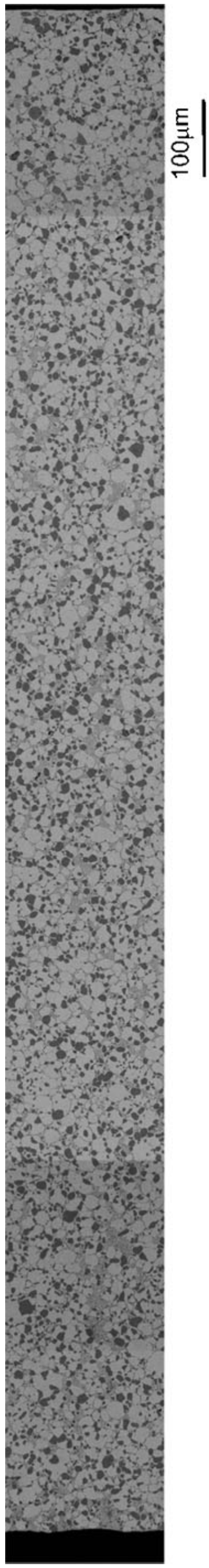
During extrusion, the melt was fed into the twin screw extruder at a constant temperature and a good control of flowrate. The melt in the clay–graphite crucible was taken out of the furnace and then put into a pot lined with insulation materials at a temperature ~10°C above its liquidus, which allow getting a stable melt temperature at 5°C above the liquidus temperature of the alloy. The melt was subsequently poured into the extruder at a good control of flowrate. Once the melt entered into the channel between the screw and the barrel, the melt was continuously sheared and cooled until it reached a solid–liquid coexisting state with the specified solid fraction level. The slurry was extruded out through an open die attached to the end of the extruder. The diameter of the extruded bar of the Zn–5 wt-%Al alloy was 4 mm, as shown in Fig. 2.

The etchant for polished samples contains 5 g CrO_3, 0·5 g Na_2SO_3 and 100 mL H_2O. The microstructure was examined using a Zeiss optical microscope with quantitative metallography and a JEOL JXA-840A scanning electron microscopy (SEM), equipped with energy dispersive spectroscopy. The shape factor F, where $F=4\pi A/P^2$ and A and P were the area and the peripheral length of the particle respectively, was used to characterise the solid phases.

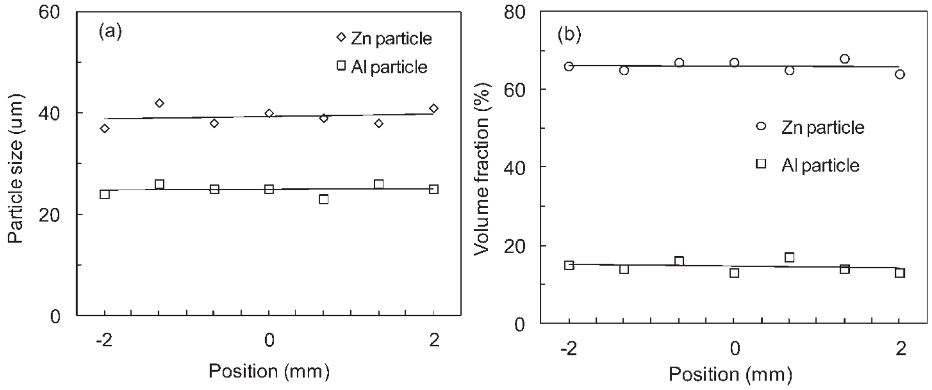
Results

The extruded 4 mm round bar of Zn–5 wt-%Al alloy was metallurgically examined on a cross-section. The montage of microstructural images is shown in Fig. 3, which demonstrates that there were three phases in the microstructure: Zn rich particles, Al rich particles and a liquid phase. Unlike the lamellar morphology formed in conventional solidification, the Zn rich and the Al rich particles exhibited a spheroidal morphology. Only a small amount of the remnant liquid in the extruded bar showed a lamellar morphology. This illustrates that, during extrusion, solidification occurred in two stages. First, the spheroidal particles were formed inside the extruder. The shearing provided convection during solidification and altered the morphology of the solid phases while forwarding the alloy from the inlet to the outlet of extruder. Second, the remnant liquid in the extruded bar solidified after exit from the open die, leading to the formation of lamellar microstructure because of the lack of convection during solidification.

The distribution of each phase was relatively uniform on the cross-section of the extruded bar, and no apparent macrosegregation was found for Zn rich particles, Al rich particles and the lamellar eutectic phase (Fig. 3). The measured particle sizes and volume fractions of the solid phases are shown in Fig. 4.



3 Photo montage of backscattered SEM images showing microstructure of extruded Zn–5 wt-%Al alloy on cross-section of 4 mm round bar (black: Al; white: Zn; fine lamellae: eutectic liquid)



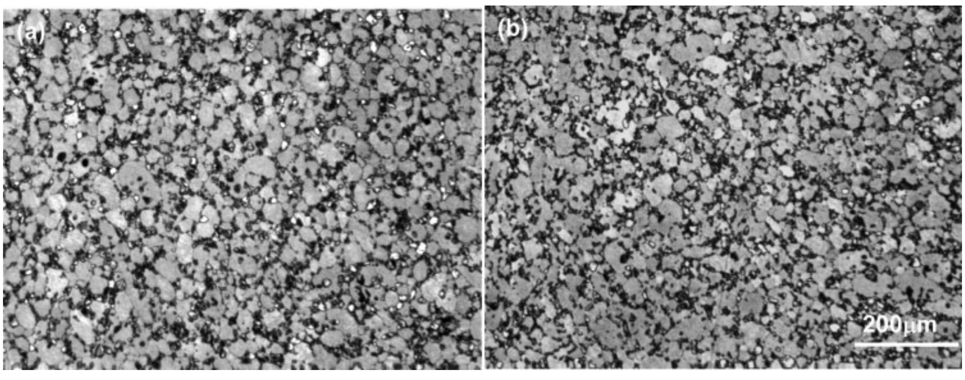
4 Particle size and volume fraction of Zn and Al rich particles on cross-section of extruded Zn–5 wt-%Al alloy

Throughout the cross-section, the solid particles were consistent in size at 40 μm for Zn rich particles and 25 μm for Al rich particles. There was no reduction and apparent variation at the edge of the extruded bar. The volume fractions were also consistent at 65% for Zn rich particles and 14% for Al rich particles. The results confirmed that two kinds of solid phases, both with good uniformity on the cross-section, were achievable in the semisolid extrusion of a eutectic alloy.

The results also confirmed that the extruded round bars of Zn–5 wt-%Al alloy have acceptable surface qualities. The microstructures of the extruded bar were examined in both longitudinal and transverse sections. The micrographs in Fig. 5 show that the globular microstructure existed in both of the two sections. The spheroidal Zn rich and Al rich particles were distributed both uniformly and independently within the matrix, and there was no apparent plastic deformation in the extruded alloy. The size of the solid particles was at the same level in both the longitudinal section and the transverse section for two solid phases, although the Zn rich particles were obviously larger than the Al rich particles in the microstructure. The results shown in Figs. 2–5 illustrate two important features in the semisolid extrusion of a eutectic alloy: the independent distribution of two kinds of solid particles within the extruded products and the similar microstructure observed in both the longitudinal and transverse sections.

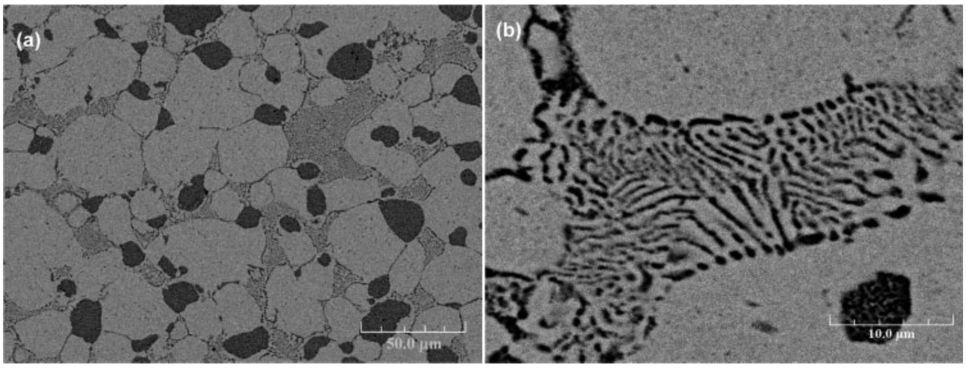
In the semisolid extrusion of a eutectic alloy, the final microstructure may include the lamellar morphology of eutectics. This is found within the remnant liquid in the alloy, which solidifies after exiting the open die attached at the end of the extruder. The amount of remnant liquid in the microstructure can be controlled during extrusion by the barrel temperature. Figures 6–8 show the microstructure of an extruded eutectic alloy at different barrel temperatures. In Fig. 6, the barrel temperature was 375°C, and the resultant remnant liquid level was 9%. The liquid exhibited the typical lamellar eutectic morphology in the final microstructure. The solid particles in the microstructure continued to have good sphericity of both the Zn rich and the Al rich particles, and no plastic deformation was observed. The edges between the solid Al rich particles, the solid Zn rich particles and the liquid phase were clear.

When the barrel temperature was reduced to 370°C, the amount of liquid in the extruded eutectic alloy also reduced to 2%. The remnant liquid solidified to form fine lamellar morphology in the final microstructure (Fig. 7*b*). Interestingly, some of the Al rich particles were surrounded by a fine lamellar eutectic microstructure that bridged the Al rich and the Zn rich particles (Fig. 7*c*). This was believed to be caused by the eutectic liquid film solidifying after the alloy exited the open die. In this case, the solid Al rich and Zn rich particles still showed no apparent deformation (Fig. 7*a*). The existence of liquid film on the solid Al rich particles would significantly reduce the extrusion force without damaging the formability of the alloy during extrusion. One should note that the eutectic spacing was quite different for the eutectics in Fig. 7*b* and that those in Fig. 7*c* because a much smaller eutectic spacing existed on the surface of the solid particles. The eutectic layer surrounding the



a longitudinal section; *b* transverse direction

5 Optical micrographs showing microstructure of Zn–5 wt-%Al eutectic alloy extruded at 370°C and 2040 s^{-1} (black: Al; grey: Zn)



a morphology of Al rich and Zn rich particles with eutectics; *b* enlarged image showing lamellar eutectic microstructure

6 Backscattered SEM images showing microstructure of Zn–5 wt-%Al alloy extruded at 375°C and 2040 s^{-1} (black: Al; white: Zn; fine lamellae: eutectic liquid)

solid Al rich particles occurred in a very small processing temperature window. In the meantime, many solid Al rich particles still showed a clear edge and no liquid film in their surroundings (Fig. 7*b*).

When the barrel temperature was further reduced to 365°C, no remnant liquid around the solid particles was observed, and the shape of Al rich particles changed from a spheroidal to an irregular morphology (Fig. 8*b*). This implies that some plastic deformation occurred during the extrusion process. The volume fraction of the Zn rich and the Al rich particles increased, but the volume fraction of remnant liquid decreased when decreasing the barrel temperatures in the experimental range. Meanwhile, the particle size was close to 40 μm for Zn rich particles and 25 μm for Al rich particles, while the shape factor slightly reduced at the same time.

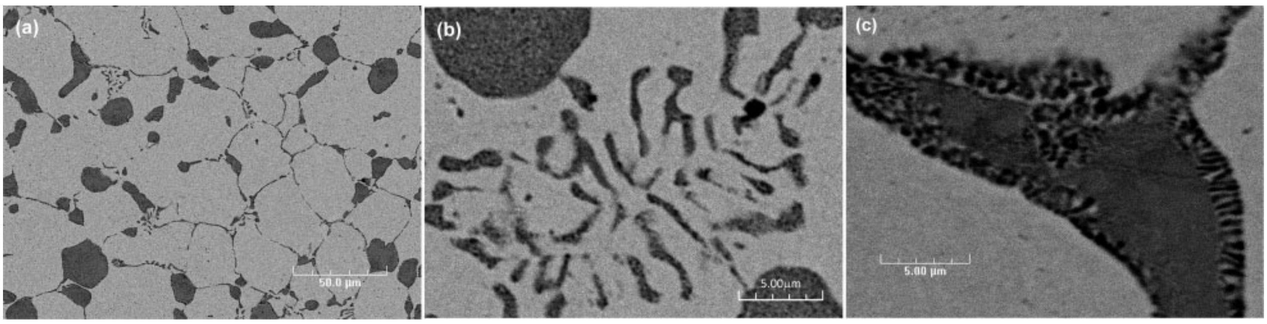
The combined analytic results of the different phases at the different barrel temperatures are presented in Table 1. These results confirm that a eutectic alloy could be extruded in a semisolid state by controlling the barrel temperatures in the extruder. The eutectic alloy was cooled down and sheared to form semisolid slurry before entering the open die to form the extruding profile. Therefore, lower shearing temperatures in the twin screw extruder can not only reduce the amount of remnant liquid in the alloy but also introduce plastic deformation during extrusion.

An increase in the amount of solid phases in the eutectic alloy during extrusion would increase the shearing force in the extruder. Figure 9 shows the shearing torques as a function of the barrel temperature in the twin screw extruder. The results confirmed that the shearing torque increased significantly as the barrel temperature of the extruder decreased. A much higher shearing torque occurred at a barrel temperature of 365°C than that at 375°C. Obviously, the higher torque implies that higher deformation energy has been introduced into the alloy. In addition, it is understandable that a higher shear rate would result in a lower shear torque because of the pseudoplastic performance of the sheared slurry in the extruder.

It should be emphasised, however, that the barrel temperature did not equal the temperature of the alloy during extrusion. Normally, the shearing temperature of the alloy is higher than the barrel temperature in the extrusion because of the existence of a barrier to heat transfer during processing. When the semisolid slurry was sheared at a high volume fraction, it was difficult to measure the precise shearing temperature for the alloy because of the friction between the tip of the thermocouple and the semisolid slurry inside the extruder. However, the increased shearing torque at lower barrel temperatures clearly indicates the increased solid phase in the semisolid slurry.

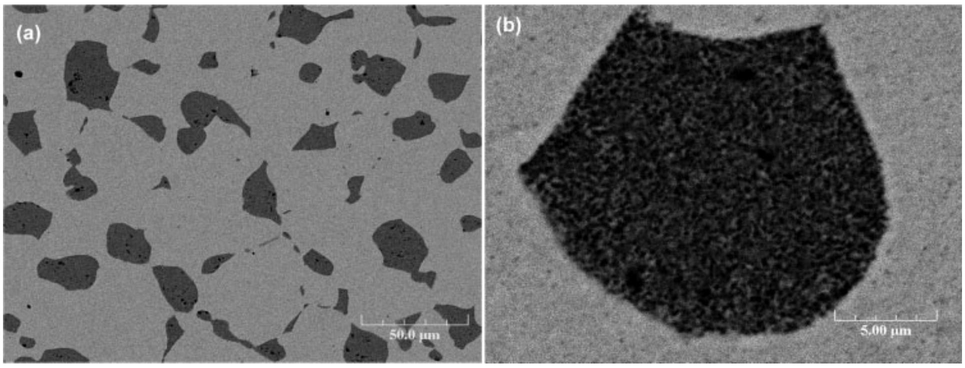
Discussion

Experimental observations originally established that semisolid extrusion using a twin screw extruder can produce a unique microstructure for binary Zn–Al eutectic alloys. The conventional lamellar microstructure is completely altered in the extruded alloy. Two types of global solid particles are created inside the extruded product. The microstructure is controllable by



a morphology of Al rich and Zn rich particles with lamellar eutectics; *b* enlarged image showing lamellar eutectic microstructure; *c* enlarged image showing lamellar eutectic microstructure in surroundings of Al rich particles

7 Backscattered SEM images showing microstructure of Zn–5 wt-%Al alloy extruded at 370°C and 2040 s^{-1} (black: Al; white: Zn; fine lamellae: eutectic liquid)



a morphology of Al rich and Zn rich particles; *b* enlarged image showing deformed Al rich particles
8 Backscattered SEM images showing microstructure of Zn–5 wt-%Al alloy extruded at 365°C and 2040 s^{-1} (black: Al; white: Zn)

altering the barrel temperature, which determines the amount of liquid in the extruded product. The formation of the unique microstructure can be attributed to the unique flow behaviour of the materials in the twin screw extruder and the microstructural evolution during extrusion.

Material flow within twin screw extruder

The various types of extrusion have a common feature of forcing the material, located in a wider cross-section, through the restricted width of a die. Therefore, the approach to understand the process of material flow during twin screw extrusion can be divided into two areas: the feeding and conveying of the material within the twin screw extruder and entry and flow through the extrusion die (the downstream processing is also important for the quality of the final product, but it will not be discussed here because it is beyond the scope of the present paper). These two areas require different considerations, such as the flow of material, shear force, residence time and pressure, cooling rate and shaping.

Twin screw extruders offer improved feeding ability and increased positive conveying characteristics: they can process slippery materials and yield short residence times from inlet to outlet, and they have enhanced temperature control with a larger heat transfer area and mixing capacity. The conveying process in closely self-wiping corotating twin screw extruders can be illustrated by the simplified flat model in Fig. 10. The down channel length of each flat screw segment is $S/\sin \varphi$, where S is the pitch of the screw flight and φ is the helix angle. The screws are offset in a cross-channel direction by a distance X_0, where X_0 is often taken to be equal to the cross-channel flight width.

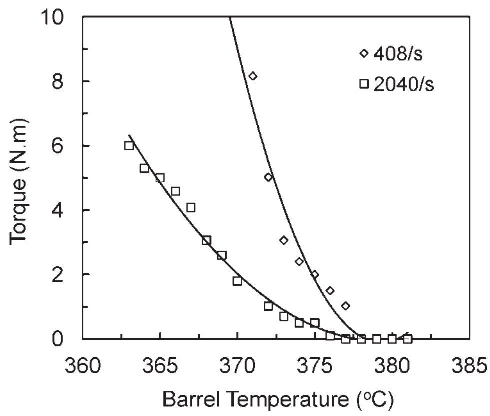
Table 1 Mean particle size, volume fraction and shape factor of Zn rich and Al rich particles in extruded Zn–5 wt-%Al alloy at different processing temperatures

Barrel temperature/°C		375	370	365
Volume fraction/%	Zn rich particles	60	67	70
	Al rich particles	12	14	18
	Remaining liquid	9	4	0
Mean particle size/μm	Zn rich particles	35	39	46
	Al rich particles	20	22	29
Shape factor	Zn rich particles	0·71	0·64	0·54
	Al rich particles	0·74	0·68	0·51

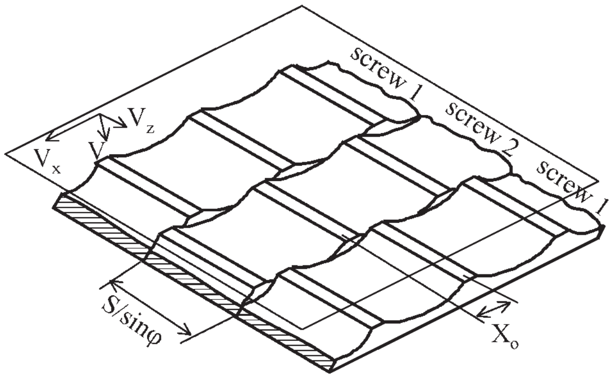
Obviously, this model is a severe simplification of the actual conveying process because it cannot actually represent the interscrew material transfer in the intermeshing region. However, it introduces an idea to help understand the twin screw extruder. As shown in Fig. 10, the degree of positive displacement in the twin screw extruder depends on how well the flight of screw 1 closes the opposing channel of screw 2. The existing gap between them (roughly defined by X_0) serves not only to reduce the degree of positive displacement but also to increase the shear on the slurry.

The mixing characteristics and overall behaviour of the slurry are primarily determined by the leakage flows occurring in the intermeshing region. The screw velocities in the intermeshing region are in opposite direction; therefore, material entering the intermeshing region will have little tendency to move through the entire intermeshing region, unless the flight flank clearance is quite large. In addition, because of the open area between the channels, the material entering the intermeshing region will tend to flow into the channel of the adjacent screw. The material will, therefore, move in 'figure of eight' patterns while at the same time moving in an axial direction.

The material close to the passive flight flank, however, cannot flow into the channel of the adjacent screw because it is obstructed by the flight of the adjacent screw. This material will undergo a circulatory flow. The higher the rotating speed and the wider the flight, the smaller and the faster the resulting circulating flow. In this continuous flow field, the fluid undergoes cyclic



9 Shearing torque as function of barrel temperature during extrusion of eutectic Zn–5 wt-%Al alloy



10 **Flat plate model in closely self-wiping corotating twin screw extruders (X_0: offset of screw in cross-channel direction; S: pitch of screw flight; φ helix angle)**

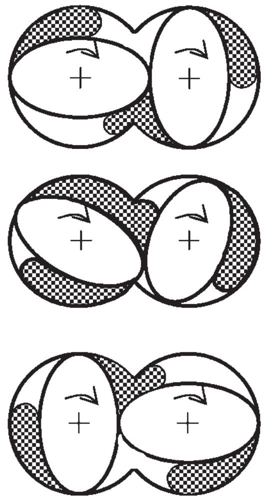
stretching, folding and reorienting processes. This is shown schematically in Fig. 11, with respect to the streamlines during the takeover of the materials from one screw to the other, which make the semisolid slurry being continuously and severely deformed. This leads to the formation of the unique microstructure of the eutectic alloys processed by the extruder.

The corotating twin screw extruder has a sliding type of intermeshing, resulting in high pressure regions at the point where the material enters the intermeshing region. The pressure build-up depends on a few factors, such as the geometry of flight, the rotating speed and the viscosity of material. The pressure will result in lateral forces on the screws that try to push the screws apart. The separating force will, in turn, reduce the gap between the screw and the barrel, resulting in a further increase in the shear rate in the twin screw extruder. The pressure also pushes the sheared metal through the extrusion die to form different profiles.

Microstructural evolution of eutectic alloys during twin screw extrusion

For semisolid extrusion of eutectic alloys, the phases presented in the binary alloy are essentially the same as those obtained under conventional solidification: solid solution α and solid solution β. However, the semisolid extrusion of a eutectic alloy is morphologically unique and essentially different from that created by conventional solidification, where a lamellar morphology is formed. The typical feature of the extruded eutectics is the coexistence of two kinds of fine and spheroidal particles in the matrix. These particles exhibit a similar morphology and distribute uniformly within the matrix on the cross-section of extruded bar (Fig. 3).

In off eutectic alloys, the formation of a non-dendritic structure, via shearing the alloy at a temperature below liquidus and above solidus, has been summarised by Fan[4] and Flemings.[19] The globular primary phase can be rosettes or spheroidal particles depending on the intensity of shearing during solidification. The proposed mechanisms include cellular growth,[20,21] dendrite fragmentation,[22] recalescence[23,24] and spheroidal growth.[18] It is well known that the off eutectic binary alloys only form one primary phase at the initial stage of solidification, and the microstructure shows dendrites under conventional solidification. The situation becomes more complicated for shearing eutectic alloys because the two phases solidify simultaneously and undergo coupling growth during solidification to form a lamella structure in conventional solidification.



11 **Diagram showing folding and deformation mechanisms of processing materials in twin screw extruder at different screw positions**

For the solidification of eutectic alloys under shear, the mechanisms have been discussed by Ji and Fan.[17] During extrusion, the solidification in the extruder reaches the finishing stage. A large amount of solid phases have been created in the sheared alloy during extrusion. Therefore, the friction in the alloy becomes dominant, which not only leads to the separation of the different solid phases but also generates heat inside the alloy under shear.

The energy balance is the main consideration for the control process of extrusion. When a small amount of liquid exists in the semisolid slurry, the liquid will act as a lubricant to reduce the extrusion force during passing through the extrusion die. The liquid solidifies immediately after exiting the extrusion die because of the existence of the temperature gradient. Meanwhile, due to no shear, the solidification forms a lamellar structure in the conventional manner (Figs. 6 and 7). It should be emphasised that the existence of liquid film may cause quality problems because the liquid film is prone to creating cracks in the product. Therefore, the extrusion should be controlled at a point where only a little plastic deformation occurs at the exit of the extrusion die. This can give a higher dimensional accuracy in the extruded product but not significantly increase the extrusion force and energy consumption during extrusion.

Conclusions

Semisolid extrusion with a twin screw extruder has been successfully developed for eutectic alloy. In this process, the melt of a eutectic alloy is sheared and cooled down, inside the twin screw extruder, to a semisolid state and simultaneously extruded through an open die at a temperature close to solidus. The accurate control of the heat balance inside the extruder results in the formation of two solid phases and one liquid phase in the extruded Zn–5 wt-%Al eutectic alloy. A little plastic deformation in the extruded alloy can be introduced with twin screw extrusion. In semisolid extrusion, the particle size in the Zn–5 wt-%Al eutectic alloy is close to 40 μm for Zn rich particles and 25 μm for Al rich particles. The two solid particles are stable in size in both longitudinal and transverse directions and distribute uniformly and independently throughout the whole cross-section of extruded bar. The remnant liquid can act as a lubricant for reducing forces during extrusion and solidifies in lamellar morphology between the Al rich and the Zn rich particles.

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