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Flow Features and Industrial Applications of TSE Rheoextrusion Process

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Abstract: This paper presents an overview of diverse extrusion techniques and, in particular, a focused discussion about the rheoextrusion process for semi-solid casting (a novel casting process for the fabrication of high quality metals). The review reveals a wealth of interesting rheological and microstructural features, illustrating qualitative and quantitative data. The analysis is supported by relevant numerical results and examples. It is shown how numerical studies can lead to significant insights into these processes by providing more detailed information on the fundamental mechanisms of morphology development (during phase change) and profile forming. The die filling and solidification behaviours within extrusion dies are simulated numerically. The extrusion forming process is also investigated and compared with experimental results. The numerical results show that the profiles of velocity and solidified front of semi-solid metals (SSM) within the die will influence the final microstructure of casts, both in the interior and on the surface. Finally, an industrial application employing a special patented concept design is presented and analysed.

Keyword: Rheoextrusion, semi-solid metals, die filling, metal forming, solidification

1 Introduction

Extrusion is a manufacturing process widely used to produce parts and components for the construction industry (PVC window profiles, pipes and tubes), automotive industry (rubber seals, gas conducts), biomedical industry (medical tubing), textile industry (nylon fiber), etc. The twin-screw extrusion (TSE) die process for semi-solid and immiscible alloy casting was developed prototypically (Roberts et al., 2002), and has been used in the above areas as a mixing process before extrusion, and also in food processing. After flowing around the rotating twin-screw, melt material enters the final die whose function is to transform the circular flow section at the end of the screw into the complex shape of the die lip. Rheoextrusion casting by TSE provides excellent microstructure metallurgical characteristics in semi-solid and immiscible alloy casting, which are potential products for automotive components.

There is an increasing need to be able to control these complex metallurgical processes, requiring an improved capability to numerically simulate and study these processes (Amberg and Shiomi, 2005). Numerical simulations are, in principle, ideally suited to study these complex multiphase flows and provide an insight into the process that is difficult to obtain experimentally (Abhilash, Joseph and Krishna, 2006; Hong Zhu, and Lee, 2006; and Narski and Picasso, 2007). Though numerical simulators have been developed for polymer melt flow in TSE extrusion, and for the reheat metal material extrusion process, there are no available studies for the simulation of liquid metallurgical alloy flow in TSE extrusion. As this involves both complex rheological and metallurgical behaviours, these flows present interesting technological challenges.

Numerical simulation of rheoextrusion casting by TSE can be categorised into two sub-processes: the first involves the rheological behaviour of the metal flow inside TSE, where multiphase mixing and the transition from turbulent to laminar flow appear; the second sub-process is dominated by

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semi-solid flow, including solidification, die filling and metal forming processes.

The paper runs as follows: Section 2 presents a review of the existing literature; Section 3 focuses on the analysis of the rheoextrusion process; Section 4 introduces numerical methods for rheoextrusion; Section 5 shows numerical investigations and predictions; Section 6 presents design approaches for industrial applications; finally, concluding remarks are given in Section 7.

2 Literature review

Numerical simulations of extrusion processes are mainly related to melt polymers as well as applications to food and pharmaceutical processes. Numerical simulations of extrusions for metal process are carried out mainly for thixo-extrusion, including cold extrusion, hot extrusion and semi-solid extrusion. A review of applications to the extrusion bending process is not included here, but a recent review paper was published by Vollertsen et al. (1999).

2.1 Simulations of extrusion process

Extrusion is a process used to manufacture products in the form of continuous lengths with a uniform cross section. This section can be quite simple, *i.e.* circular, annular or rectangular profiles, or very complex.

Numerical simulations of extrusion have been applied successfully to various cases in polymer engineering. The aim of the simulations is to investigate the following aspects:

(1) Rheological behaviour, including solid fraction, liquid pressure, temperature distribution, flow pattern, velocity profiles, filling process.

(2) Die profile design with these parameters (Carneiro et al., 2001).

(3) Extrusion shape prediction, inverse extrusion capability (Gejadze and Jarny, 2002).

(4) Process design: performance of extrusion process, cooling rate, velocity, and control temperature.

The numerical simulations are generally conducted considering the flow as viscoelastic, and are also used in the food and pharmaceutical industries (Elsey et al., 1999), to process materials such as flour (Li, 1999) and paste (Aydin et al., 2000). Typical results of numerical simulations of polymer extrusion are shown in Figure 1.

Numerical simulations of extrusion are also performed in metal processing for the investigation of metal forming, where billet aluminium alloys are materials commonly used for cold extrusion (Mehta et al., 2000; Lee et al., 2002; MacCormack and Monaghan, 2002), for hot extrusion (Skauvik, 1999; Bjork et al., 1999; Kang et al., 2002), for semi-solid extrusion (Hwang et al., 2000; Ward et al., 2000; Yoon et al., 1999), as well as for some other metals, such as magnesium (Ogawa et al., 2002). The aims of the simulations are similar to those listed above (*e.g.* die design (Hao and Li, 2000)), but more focused on defect prediction, frictional models for contacts or bearings (Lof, 2001; Lee and Im, 1999), cross-shape transforming (Celik and Chitkara, 2002), strain distribution (Liu et al., 1999), microstructure (Lee et al., 2000), etc. The main difference for metals is that numerical simulations are conducted assuming rigid viscoplastic or plastic flows (Rosochowski and Olejnik, 2002). A typical simulation result for metal extrusion is shown in Figure 2 (Mehta et al., 2000).

Simulations of liquid melts flowing through extruder dies have not appeared in the literature yet because liquid metal extrusion is a newly developed process. The simulation of rheoextrusion is different from existing extrusion simulation approaches in the following three aspects:

- Existing simulation approaches for molten flow assume a laminar viscoelastic flow, which is mostly appropriate for polymers;
- The metal flowing within a rheoextrusion die is a semi-solid, thus phase change and heat transfer dominate the whole process;
- Although rheoextrusion is a liquid metal extrusion process, it differs from conventional

Figure 1: Results of simulations using Polyflow (Polyflow, 2002)

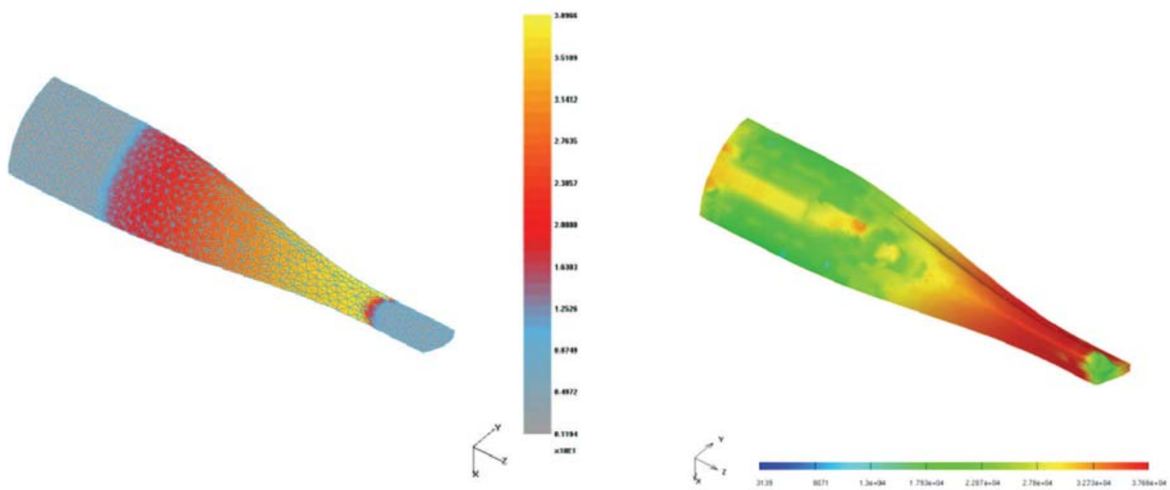


Figure 2: Effective stress distribution for a streamlined die extrusion simulation, left for DEFORM-3D®, right for MSC SuperForge (Mehta et al., 2000)

liquid casting processes involving the solidification of a pure liquid shell.

2.2 Applications of numerical simulations

There are several packages available for the numerical simulation of extrusion processes, both for viscoelastic and rigid viscoplastic flow, as shown in Table 1.

The BEM*flow* and PolyFlow codes can be used to simulate TSE and extrusion of viscoelastic flows; Polyflow, in particular, is widely used for TSE in polymer engineering. The code was developed by Polyflow s.a., founded in Belgium in 1988 and later integrated in the Fluent Inc. group in 1997. Polyflow is mostly focused on the polymer and rubber processing industry. BEM*flow* is a newly developed code based on the boundary element method. FIDAP is a widely used general CFD code which can simulate extrusion processes both for polymer and metals, *e.g.* die extrusion of aluminium (Skauvik, 1999) and continuous casting of aluminium alloys (Li, 1997). A typical example of simulation is shown in Figure 3. The most popular CAE/CAM codes are DEFORM-3D and

Table 1: Simulation software for extrusion die processes

Packages	Developer/Organization	Features		Reference
1. Commercial CFD codes for extrusion die process				
BEM*flow*	Madison Group, USA	BEM	3D, TSE polymer	(BEM*flow*)
PolyFlow	Fluent Inc., Polyflow SA, Belgium	FEM	3D, TSE polymer	(Polyflow, 2002)
FiDAP	Fluent Inc., USA	FEM	3D, metal	(Skauvik, 1999)
2. Commercial CAE/CAM codes for metal extrusion process				
MSC Superform	MSC, USA	FVM	3D, metal	
MSC Superforge	MSC, USA	FVM	3D, metal	(Metha et al., 2001; Lee et al., 2002; Kopp et al., 1999)
Deform-3D, 2D	SFTC, USA	FEM	2D, 3D, metal	(Kang et al., 2002; Lin and Lin, 2003; MacCormack and Monaghan 2002; Metha et al., 2001)
HyperXtrude	Altair Eng. Co., USA	FEM	Billet Aluminium	
ABAQUS	ABAQUS, Inc., USA	FEM	3D, metal	(Rosochowski and Olejnik, 2002; Alkorta et al., 2002)
ANSYS	ANSYS, Inc., USA	FEM	3D, metal	(Hu et al., 2000)
LS-Dyna3D	LSTC, USA	FEM	3D, metal	(Reyes et al., 2002; Langseth et al., 1999)

BEM-boundary element method, FEM-finite element method, FVM-finite volume method

MSC SuperForge. The application of finite element methods (FEM) to metal forming during the 1970s and early 1980s provided a new perspective on metal-forming practices. One such computer package, named Design Environment for Forming (DEFORM), was developed at Battelle Columbus Laboratories, USA, later Scientific Forming Technology Corporation (SFTC). SFTC was incorporated in 1991 by former Battelle employees to provide state-of-the-art process design and analysis technologies to the material forming industry. DEFORM, based on the FEM approach, is arguably the most popular package in metal forming. MSC SuperForge and SuperForm are based on the finite volume method (FVM) and were developed by MSC, a leading CAE/CAM provider. It is claimed that the FVM approach used in MSC SuperForge eliminates the meshing problems that make simulating a metal forming process with severe deformation, such as the extrusion process using a shear die, so difficult (Mehta et al., 2001).

Many in-house codes are also used in metal extrusion, such as DiekA (Lof and Blokhuis, 2002; Langkruis et al., 2000; Antúnez 2000), CAMPform (Lee and Im, 1999), SFAC2D (Hwang et al., 2000), FORGE2 (Raj et al., 2000), ALMA (Okstad et al., 2000).

Despite the availability of commercial CFD/CAE/CAM packages for the simulation of extrusion processes, including microstructure and macrostructure behaviours, there is still a limited ability to simulate the rheoextrusion process, because available approaches are either viscoelastic for continuous polymer melt or viscoplastic rigid for billet processes. The simulation of rheoextrusion involves both fluid flow/semi-solid flow and viscoplastic rigid flow; the structure of the suspension in the semi-solid phase will determine the rheofluidization, as shown in Figure 4 (Perez et al., 2000). The result is that different numerical approaches should be employed for different flow regimes. For example, the simulation can

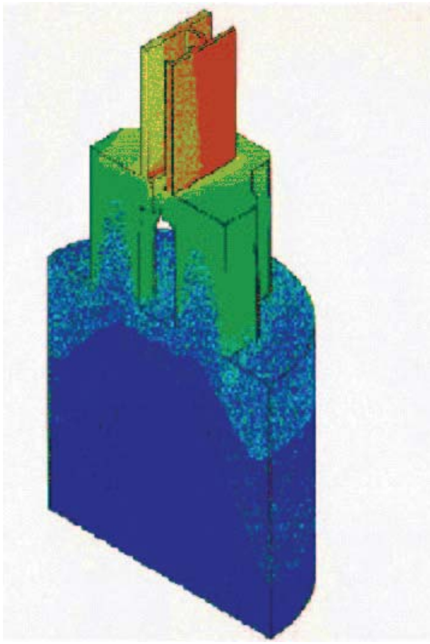


Figure 3: Fidap simulation of aluminium extrusion to improve porthole die design (Skauvik, 1999)

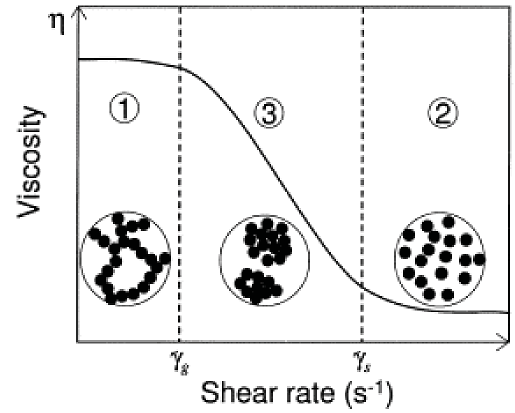


Figure 4-a: Rheofluidization: viscosity decreases with the shear rate for 1-percolating network, 2-dispersed suspension, 3-suspension of clusters (Perez et al., 2000).

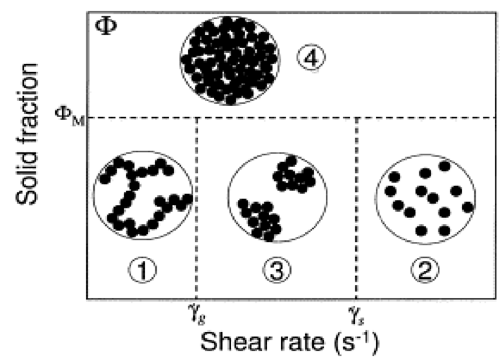


Figure 4-b: Structure of the suspension in the semi-solid phase-space. 1-gel, 2-suspension of individual particles, 3-suspension of clusters, 4-compact arrangement (Perez et al., 2000).

Figure 4: Structure of a suspension

be conduced as viscoplastic for regime 4 and solidified extrusion, as porous media flow for regime 1, and as particulate flow for regimes 2 and 3, with a discrete model for regime 2 and a discrete cluster model for regime 3.

3 Analysis of rheoextrusion process

The basic process for simulations of metal extrusion via thixoroute forming (thixoforming, thixoextrusion) is illustrated in Figure 5 (Kopp et al., 1999). The rheoroute forming process (rheomoulding, rheocasting, rheoextrusion) is a continuous process, in which there is phase change from a liquid metal to a semi-solid metal, and then to a solidified phase. This is a continuous process which is more difficult to implement numerically. The basic steps for the process of rheoroute forming are illustrated in Figure 6 (Scamans and Fan, 2005a).

3.1 Critical aspects of rheoextrusion process

Semi-solid flow process: Materials in die come from the TSE in semi-solid state; their rheological behaviour is strongly dependent on solid fraction, and the flow regime is a two-phase flow with phase change. For immiscible alloys, the flow regime is a three-phase flow.

Solidification forming process: The solidification shell is formed inside the die, ideally close to the die outlet; the material is in high solid-fraction semi-solid state, which is then extruded by a force pushing the material through the die lip to form specific shapes. The twin-screw used in the rheoextrusion process (Figure 7) has a 16 mm diameter at tip and 3 mm groove with a special profile to achieve high shear rate and enhance the

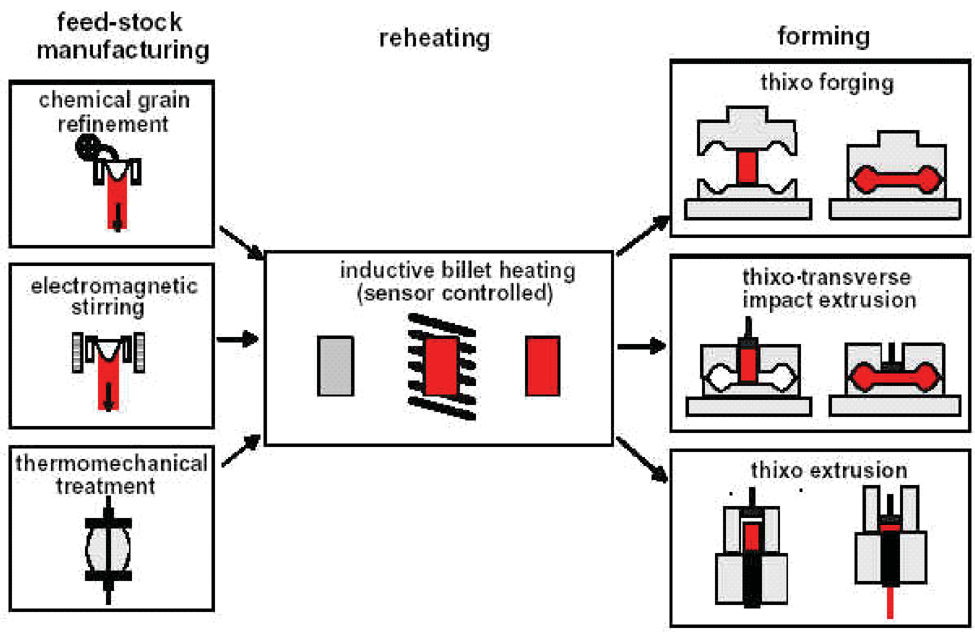


Figure 5: Process of thixo-route forming (Kopp et al., 1999).

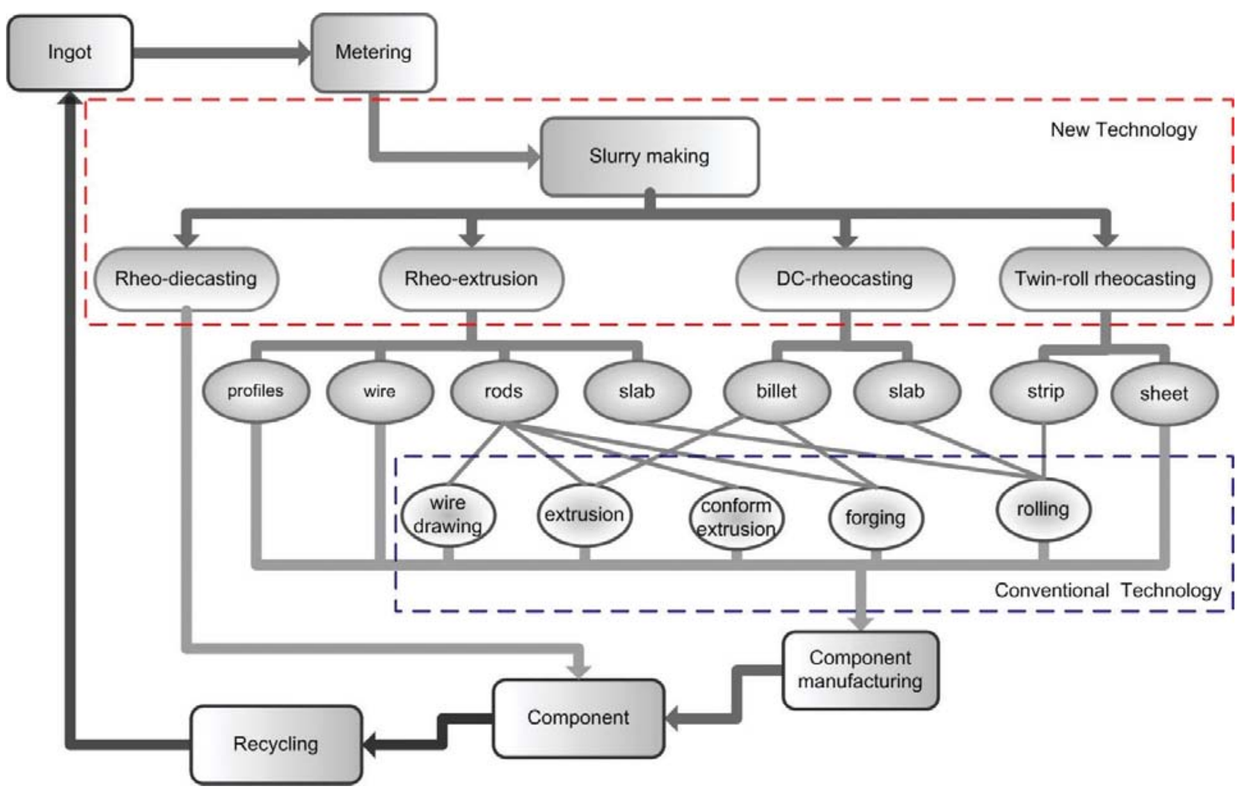


Figure 6: Flow chart of rheoroute-forming for Mg alloy (Scamans and Fan, 2005a).

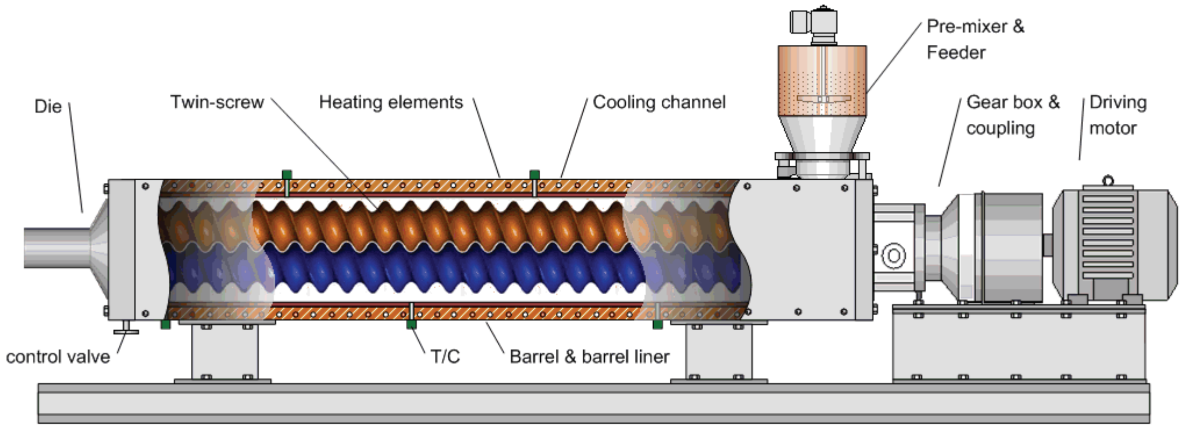


Figure 7: Schematic illustration of a prototype experimental rheoextruder

positive displacement pumping action (Fan et al., 1999). The maximum rotation speed of the screw is designed at 1000 rpm, which corresponds to the maximum shear rate at 4082 s^{-1} in the gap between the tip of the screw flight and the barrel. The rotation speed for the experimental work in the BCAST laboratory was set at 800 rpm. The status of the alloy liquid during the twin-screw processing is controlled by a temperature control system, which ensures a proper viscosity of the matrix phase from start to finish (Fan et al., 2001).

3.2 Comparison with conventional extrusion process

Figure 8 illustrates the difference between the conventional extrusion and rheoextrusion processes. Conventional extrusion is characterised by multi-step, equipment intensive, labour intensive, energy intensive, and above all, low quality and low materials yield (as low as 50%). Radically different, the rheoextrusion process is one-step; high quality extruded profiles can be produced directly from liquid Mg alloys. Therefore, it is a low-cost, simplified and high quality process. The anticipated price for rheoextruded products could be several times lower than that for the same product from the conventional extrusion process. The low-cost nature of such production technologies alone can bring billions of dollars to the global economy in the next 10 years.

4 Numerical methods

4.1 Numerical approaches

Simulations have been carried out for die filling and solidification by simplified numerical models, and the results have shown that die design and process control parameters can be optimized through numerical predictions more easily than via experiments. The thermophysical properties of alloys can be taken from Iida and Guthrie (1988), while phase equilibrium data of alloys are taken from Hultgren et al. (1973).

The solution algorithm involves the use of a control-volume-based technique to convert the governing equations to algebraic equations that can be solved numerically. Non-linear governing equations are linearized by an implicit scheme to produce a system of equations for the dependent variable in every computational cell. A point implicit Gauss-Seidel linear equation solver is then used, in conjunction with an algebraic multigrid (AMG) method, to solve the resultant scalar system of equations for the dependent variable in each cell. Pressure-velocity coupling is achieved by using the pressure-implicit with splitting of operators (PISO) scheme.

4.2 CFD approach for rheoextrusion

The die filling process is simulated by the volume-of-fluid (VOF) method that can trace the front in-

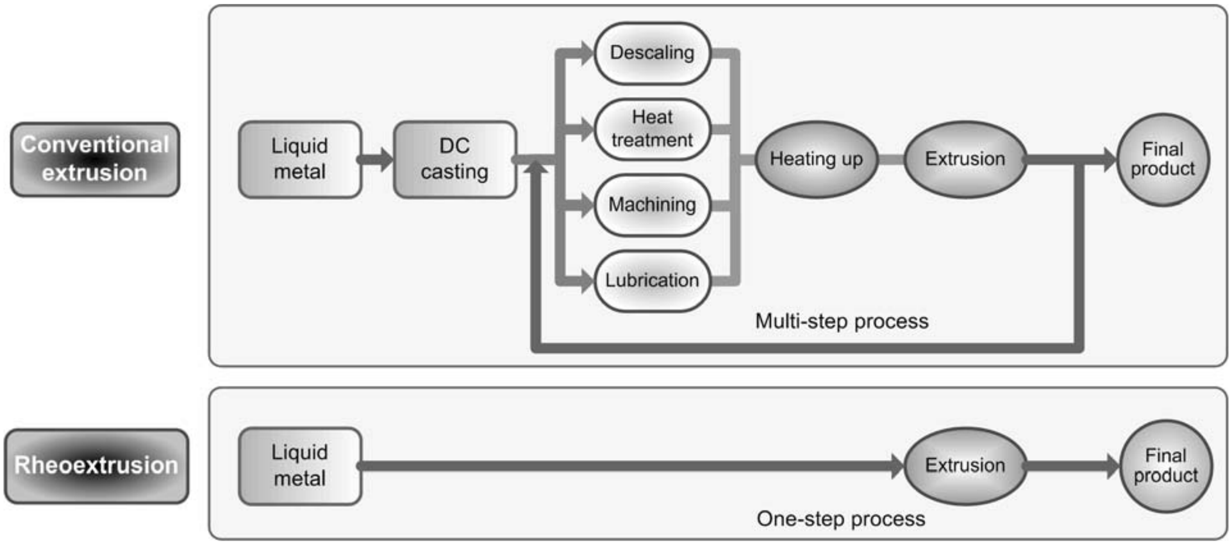


Figure 8: A comparison between rheoextrusion and conventional extrusion processes.

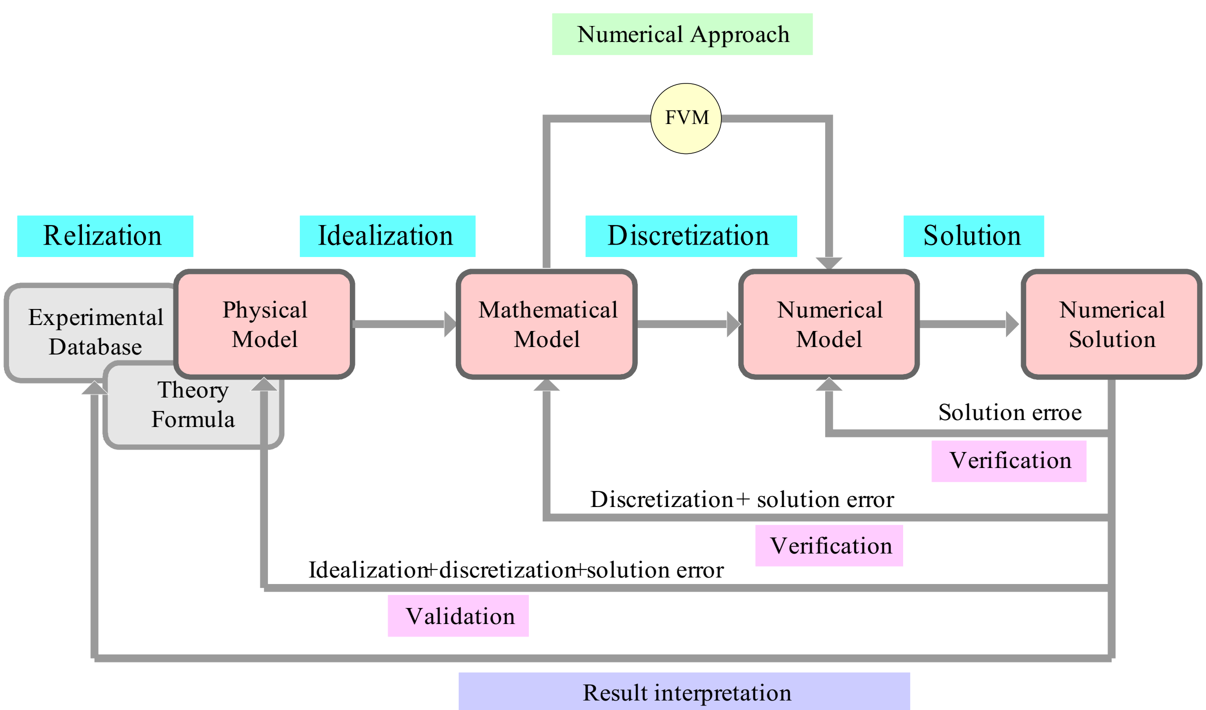


Figure 9: Schematic flowchart of simulation approach strategy

terface of die extrusion. VOF numerical methods have been reviewed and verified previously (Tang et al., 2004). The phase change model is coupled with the VOF method in order to trace the progress of the solidification front during die filling. An enthalpy-porosity technique (Voller and Prakash, 1987) is used for modelling the solidification process. The enthalpy-porosity method is a simplified approach for the movement of the solidification front, in which the melt interface is not tracked explicitly. Instead, a quantity called the liquid fraction, which indicates the fraction of the cell volume that is in liquid form, is associated with each cell in the domain. The liquid fraction is computed, at each iteration, based on an enthalpy balance. The mushy zone is a region in which the liquid fraction lies between 0 and 1. The mushy zone is modelled as a "pseudo" porous medium in which the porosity decreases from 1 to 0 as the material solidifies. When the material has fully solidified in a cell, the porosity becomes zero and hence the velocities also drop to zero. For more detail, see Voller and Prakash (1987) and for industrial applications, see Ludwig et al. (2005).

Figure 9 shows a schematic flowchart of the simulation approach strategy applied in the present study.

5 Numerical predictions of rheoextrusion process

5.1 Filling process

Simulations of the filling process are illustrated in Figure 10. The materials interface in the die is tracked by the VOF method. The filling time will be dependent on inlet velocity, die geometry and surface roughness. The internal velocity profile will affect air entrapment, which depend on inlet velocity, viscosity, and die geometry. High inlet velocity, non-uniform internal velocity profile, large die angle are factors that can easily cause air entrapment. Comparing internal velocity profiles for different inlet velocities at the converged section of the die, as shown in Figure 11 (left), velocity profiles are more uniform at low inlet velocities than at high inlet velocities for which it becomes easier to entrap air that could increase the porosity in the surface or inside the final product. The die design can be modified to improve the flow field, as shown in Figure 11 (right), where the ratio of convergence is reduced in order to obtain more homogenous velocity profiles and avoid air entrapment at the throat.

5.2 Solidification process

Solidification occurs during rheoextrusion and strongly depends on the external cooling condition. The solidified material shells during extrusion for different cooling conditions are depicted in Figure 12. A weak cooling condition results in that no solidified shell is formed before materials are extruded out of the die (Figure 12 a). Overcooling results in that a solidified shell is formed deep into the die, which will cause extra extrusion loads (Figure 12 b). The ideal cooling condition is that in which a solidified shell is formed near the die outlet (Figure 12 c), requiring a lower extrusion load and thus being suitable to form complex shape products. The temperature contours at ideal cooling conditions are shown in Figure 12 d, where temperature profiles within the die have a peak and then flatten after the die

5.3 Comparison with experiments

The cooling condition depends on many parameters, including the thermodynamic parameters of the extrusion and die materials, and the forced cooling method. Insufficient cooling will cause forming problems as illustrated in Figure 13. The solidified shell is not formed in Figure 13 (left) before materials are extruded out of the die, while a fold was formed due to weak cooling during extrusion in Figure 13 (right). Overcooling will cause difficulties on extruding complex shapes.

5.4 Discussions

Two key advantages of the simulation approach are illustrated above. The first is that the simulation provides a much greater range of information throughout the domain of interest, rather than at the small number of points which can be measured through physical tests, providing a better understanding of the rheoextrusion process and its sensitivity to various design parameters than was

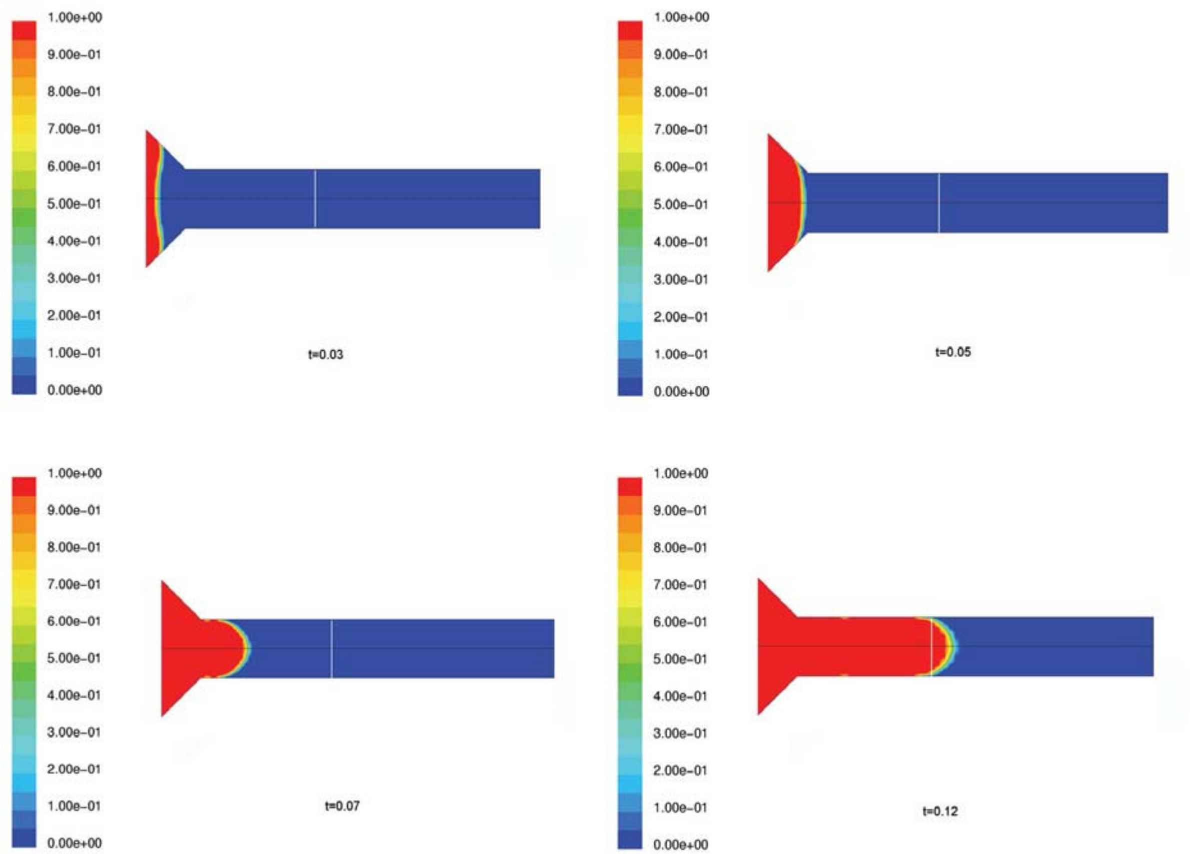


Figure 10: Simulation of filling process in die extrusion at different time steps.

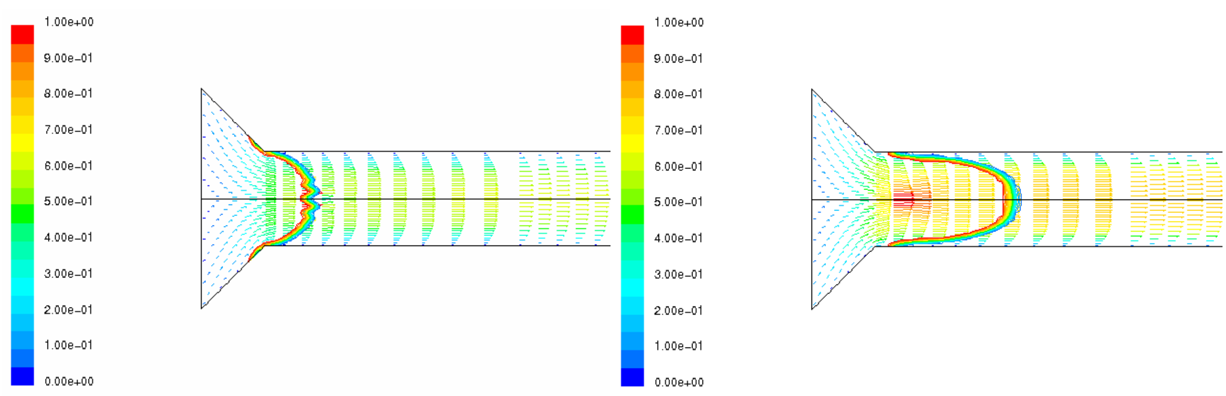


Figure 11: Comparison of velocity profiles at converged section of die for different inlet velocities; left graph is for low inlet velocity, and right graph is for high inlet velocity. Velocity profiles are more uniform in the left graph, and there is less chance for entrapping air to form porosity.

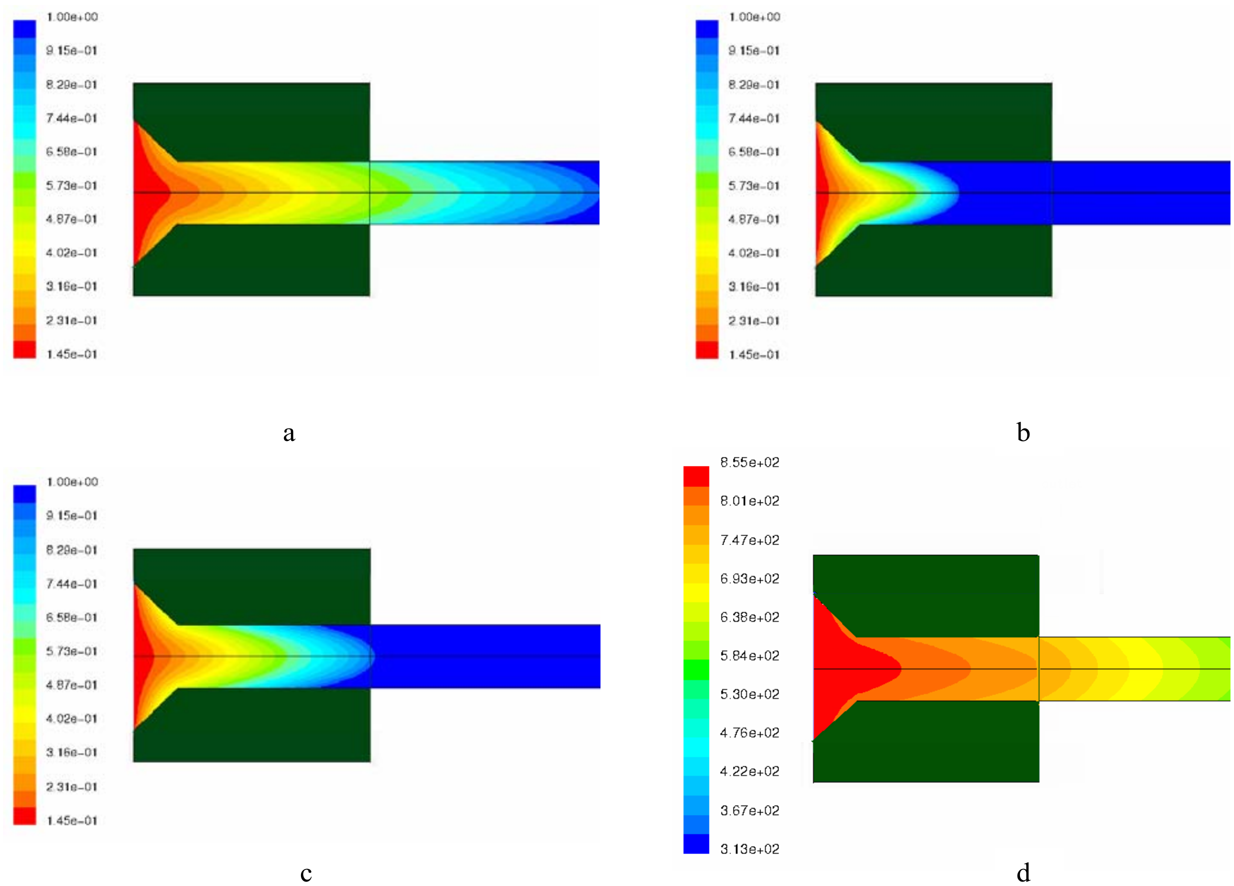


Figure 12: Comparison of solid fraction contours for different cooling conditions. The solidified shell was formed for a weak cooling condition (a), strong cooling condition (b), ideal cooling condition (c) and corresponding temperature contours (d).

ever possible to obtain experimentally. Second, simulation makes it possible to evaluate a large number of alternative die designs and process parameters, without the time and expense required to actually build and test them.

Results show that the numerical method was able to simulate the rheological behaviour of SSM alloy in rheoextrusion process. The rheological behaviour of the filling and solidification phases in rheoextrusion process was demonstrated, and qualitative agreement of the defect analysis can be achieved by comparison with experimental results, as shown in Figures 13 and 14. The preliminary model can be used to obtain an insight into extrusion load, cooling rate, temperature distribution and velocity profiles, thus providing a guide to the operating condition of rheoextrusion in order to reduce trial and error experiments for parameter optimisation.

6 Approaches for Industrial Applications

6.1 Analysis of industrial applications

Extrusion of Mg alloys is used to produce long, straight, semi-finished Mg products. Pressure is applied hydraulically by a ram to the back of a heated billet (300–400˚C) and the metal is squeezed through a die into the desired configuration. An extrusion pressure of 850 to 900 MPa is sufficient for extrusion of most Mg alloys into intricate shapes. During extrusion of Mg shapes, quality and production rate are affected by several variables, which include the geometry and complexity of the shape, the reduction in area,

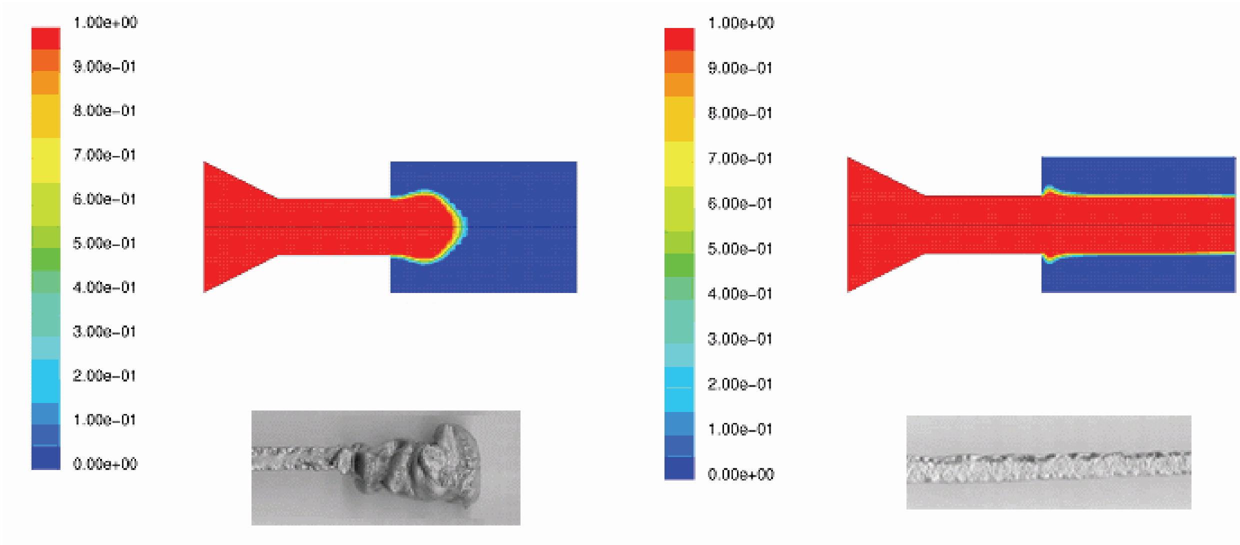


Figure 13: Possible forming problems due to poor cooling. The solidified shell is not formed before materials are extruded out of die (left). A fold was formed due to weak cooling during extrusion-case 1 (right). Numerical simulations are shown on top, experimental results (Fang, 2003) are shown below.

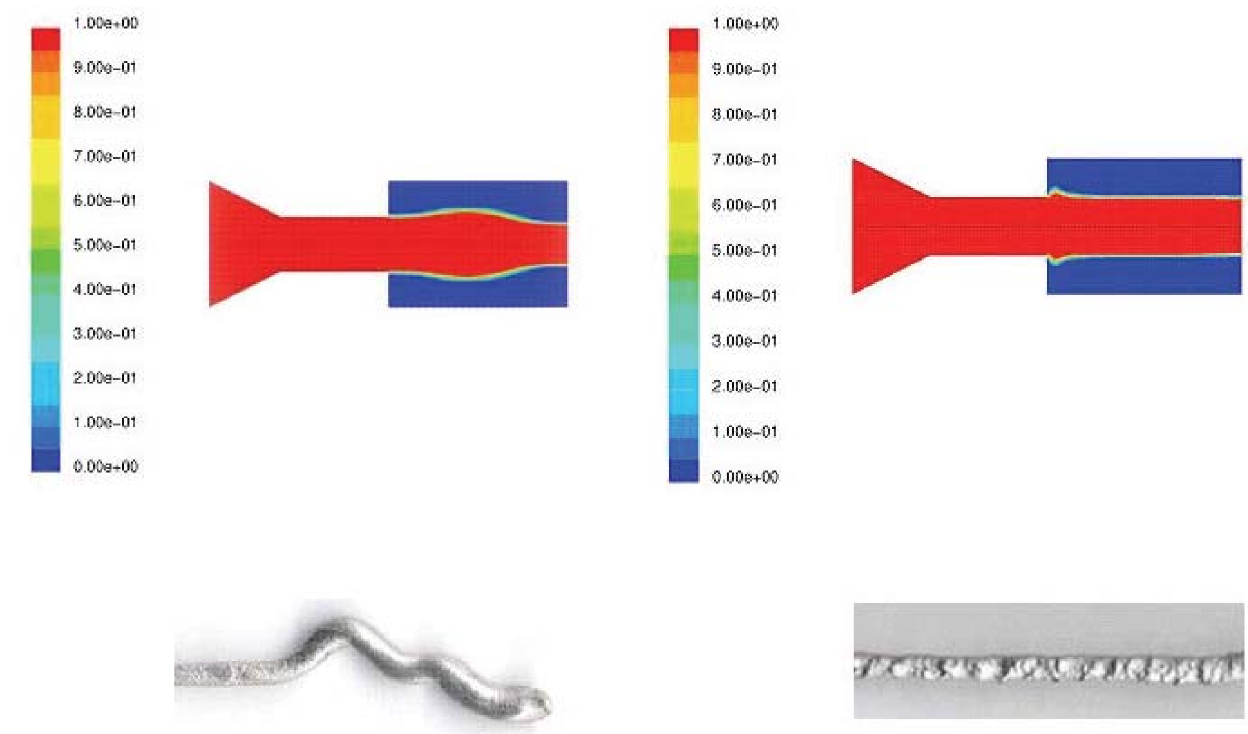


Figure 14: Comparison of numerical simulations and experimental samples (Fang, 2003). The solidified shell is not formed before materials extrude out of die (left). A fold was formed due to weak cooling during extrusion-case 2 (right).

the alloy being used, the temperature at which the extrusion is being produced, and the design of the die. With fixed-die design and a given alloy, extrusion temperature and extrusion rate can be optimised. In principle, the higher the operating temperature the faster is the extrusion rate. However, the billet temperature is limited by the hot-shortness temperature of the alloy being used. The hot-shortness temperature is defined as the temperature at which the lowest melting component in the alloy begins to melt. This molten material causes the product to tear during extrusion. Frictional forces during the extrusion process will also lead to overheating and hot shortness. Under any circumstances the onset of hot shortness must be prevented, as this leads to a direct loss of production. Therefore, the extrusion speed of magnesium has to be kept low, in the order of 1 to 20 m/min, depending on the type of alloy and the processing conditions. For comparison, aluminium extrusion speeds can be as high as 100 m/min.

The rheoextrusion process is schematically illustrated in Figure 15. The rheoextrusion equipment consists of a number of twin-screw slurry makers, a slurry accumulator, a rheoextruder and an extrusion die. The twin-screw slurry makers and the slurry accumulator form the slurry supply system. Liquid Mg alloy is sequentially fed into the slurry maker whereby it is transformed into high quality semi-solid slurry with a designated solid fraction. The semi-solid slurry is then transferred into the slurry accumulator, from which the slurry is fed continuously into the rheoextruder for extrusion. Although the twin-screw slurry makers work in a cyclic manner, rheoextrusion is a continuous process. By using different extrusion dies, the rheoextrusion process can be designed to produce rods and slabs for further processing and profile extrusions for direct component construction (see Figure 16, from Scamans and Fan, 2006a).

The generic characteristics of the rheoforming process include low cost, high material yield and fine and uniform microstructure over the entire cross section. It is the fine and uniform overall microstructure that makes the rheoformed products advantageous as quality feedstock materials for further solid-state forming, such as extrusion, rolling, forging, wire drawing and conform extrusion. Possible design approaches for industrial applications are shown in Figure 17 (Scamans and Fan, 2005b, 2006b).

6.2 Comparison of industrial processes

During the rheoextrusion process, liquid metal is fed into the twin-screw extruder with a controlled feeding rate through a liquid metal pump and cooled and sheared simultaneously to produce the desirable SSM slurry. The SSM slurry is then passed to a gear pump to regulate the extrusion pressure and speed. The extrusion die acts as a device for the final solidification and for creating the final profile.

The rheoextrusion process has the following advantages in comparison with conventional hot extrusion:

- Lower extrusion pressure(1/10—1/5 of conventional hot extrusion)
- Higher extrusion ratio possible
- Longer die life due to low extrusion pressure
- Complex cross-sectional profile
- Fine and uniform microstructure on the extrudate cross-section
- Feasible for alloys with poor deformability
- Lower cost
- Higher production rate

Both rheoextrusion and continuous rheocasting are processes designed for the production of continuous products. Table 2 compares the major differences between these two processes (Fan, 2002).

7 Concluding remarks

This paper presented a numerical investigation and industrial analysis of the rheoextrusion process. The investigations have revealed a wealth

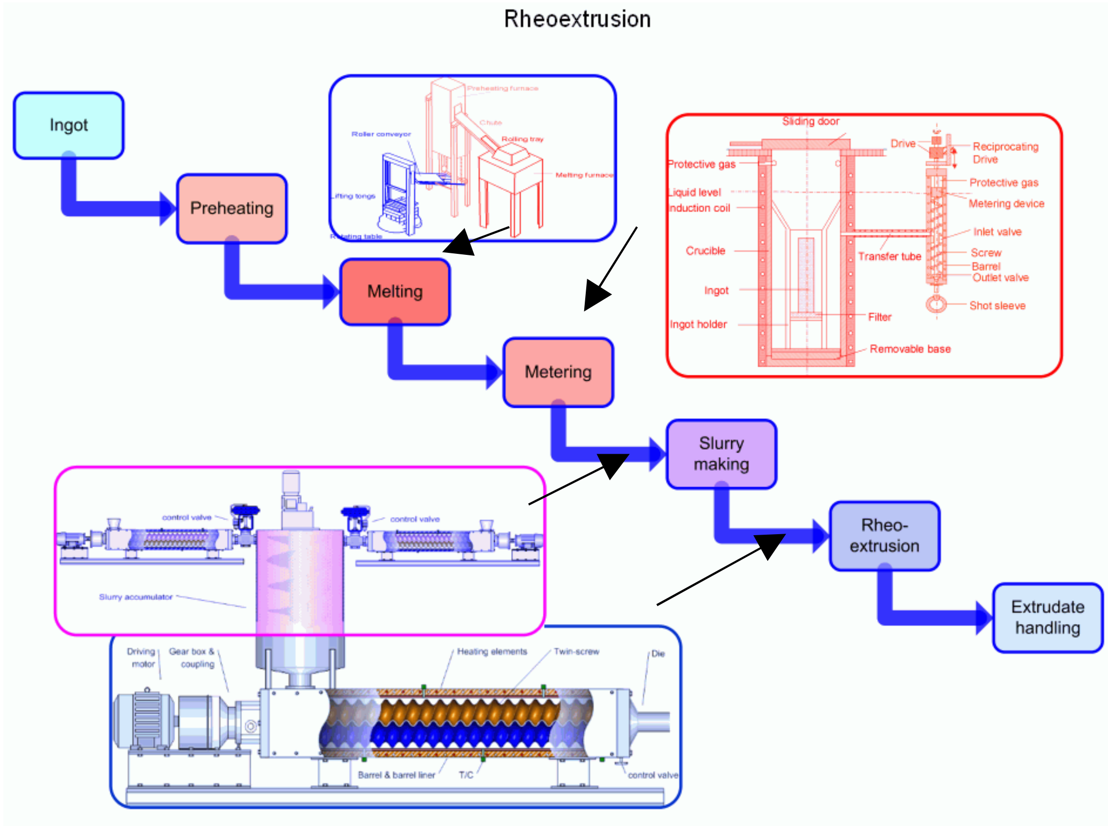
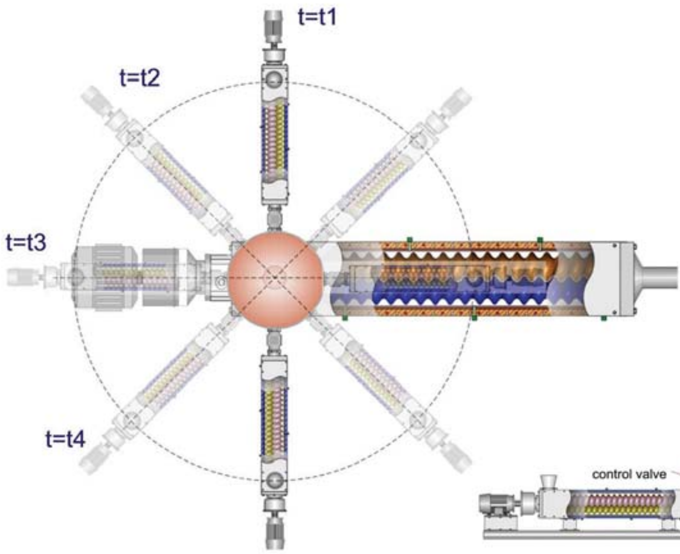


Figure 15: Flowchart of rheoextrusion process for industrial applications

Table 2: Comparison between rheoextrusion and continuous rheocasting processes

Process	Rheoextrusion	Continuous rheocasting
Shaping device	Extrusion die	Water cooled Cu-mould
Suitable solid fraction	High (>0.6)	Low (<0.3)
Cross-section	Small, sheet, complex, profile	Large, simple
Suitable alloy	Wrought, thixo-alloys	Cast, rheo-alloys
Equipment	New	Compatible with existing DC casting machine
Field of application	Automotive, consumer goods	Thixotropic feedstock, general engineering

of interesting rheological and microstructural features, providing qualitative and quantitative insights into the rheoextrusion process which are consistent with experimental work. A practical process was discussed and a possible arrangement was designed for industrial applications based on a successful prototype experimental device, since the creation of desirable SSM slurry is crucial to the quality of production and maintenance of the microstructure. Volume fraction of the semi-solid slurry was significant to the success of the rheoextrusion process and found to be a quantifiable parameter to desirable slurry. Continuation of trials to improve the understanding of the rheology and mechanical properties created by the rheoextrusion process is the natural step from this early development work, which was patented for further commercial applications. The potential reduction in both process cost and complexity over that of traditional techniques is an incentive to industrial application. The ability of rheoextrusion to produce high tolerance, complex profiles and net-shaped products leaves the process well suited to many industrial tasks.



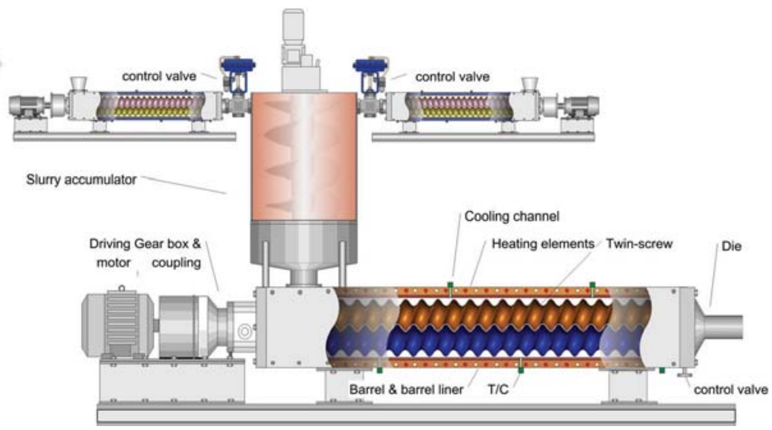


Figure 16: Schematic illustration of arrangement for rheoextrusion device (Scamans and Fan, 2006a)

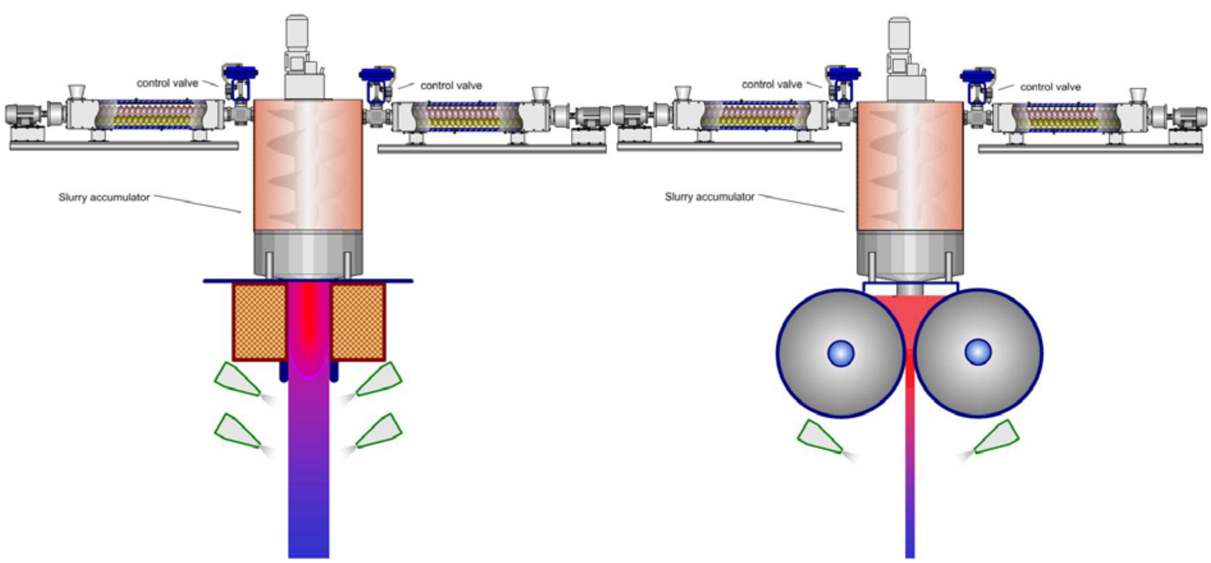


Figure 17: Conceptual designs of industrial applications of DC-rheoextrusion (left) and twin-roll rheoextrusion (right) (Scamans and Fan, 2005b, 2006b)

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