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Jetting in metal injection moulding of 316L stainless steel

P. Dvorak, T. Barriere and J. C. Gelin

The jetting phenomenon in metal injection moulding (MIM) has been investigated. To date, the behaviour of the polymer metallic powder melting during filling stage that causes problems in choosing process parameters has not been adequately described in the literature, the manner of the melt flows inside a die cavity is not easy to predict. In order to better understand the process, an experimental mould with replaceable inserts including a window glass section was designed and manufactured in our lab. The glass window allows monitoring the manner of the melt flows in real time and permit to record it with a charge couple device (CCD) camera. In this paper, the injection moulding experiments have been performed to test the filling process and occurrence of jetting. The experiments indicate that there is high probability of conventional jetting depending on process parameters. Various gate cross sections and runner length die cavity were employed as variable parameters in order to investigate their influence on jetting phenomenon. The processing regimes were kept the same during all the experiments. PM/1172

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INTRODUCTION

The metal injection moulding (MIM) process is suitable for manufacturing relatively small and complex components requiring high strength and cost viability in a large batch.

The metal injection moulding process combines the shape making capability of plastic injection moulding with the material flexibility of powder metallurgy. Using fine metallic powders in combination with a polymeric binder system, components are moulded by injection, then the polymeric binder is removed by debinding and the resulting parts are sintered by thermal effects. This process produces high density, complex and accurate shaped parts exhibiting the desired properties. The MIM technology offers advantages over conventional metal cutting or metal

forming processes, when high volume associated to complex geometry and low costs are required.¹⁻⁴

Generally, the feedstock that is used for MIM consists of a mixture of metallic powders and a thermoplastic binder. For the injection aspects, the metallic powders added to the organic binder are assumed to have an effect on two main physical properties, it increases thermal conductivity and modifies viscosity of the feedstock.

The binder component gives the mixture compound the flow characteristics of a highly thermoplastic fluid. It means that with injection moulding machines, one can process moulding of feedstock in moulds with complex geometries, for the parts as in standard thermoplastic polymer injection.^{5,6}

The MIM components weight range varies from 0.01 to 150 g.^{1,2} Mould design may consist of either single or multiple cavities depending upon the estimated processed volume and production range. With the MIM process, a green part containing plastic and metallic powders is obtained during the injection moulding stage. In the second stage, thermal, chemical or solvent debinding systems are employed to remove the binder from the green part. The resulting part (brown) is then converted into a dense metallic part by solid state pressureless sintering or liquid phase sintering. During the sintering stage, an important volumetric shrinkage occurs.

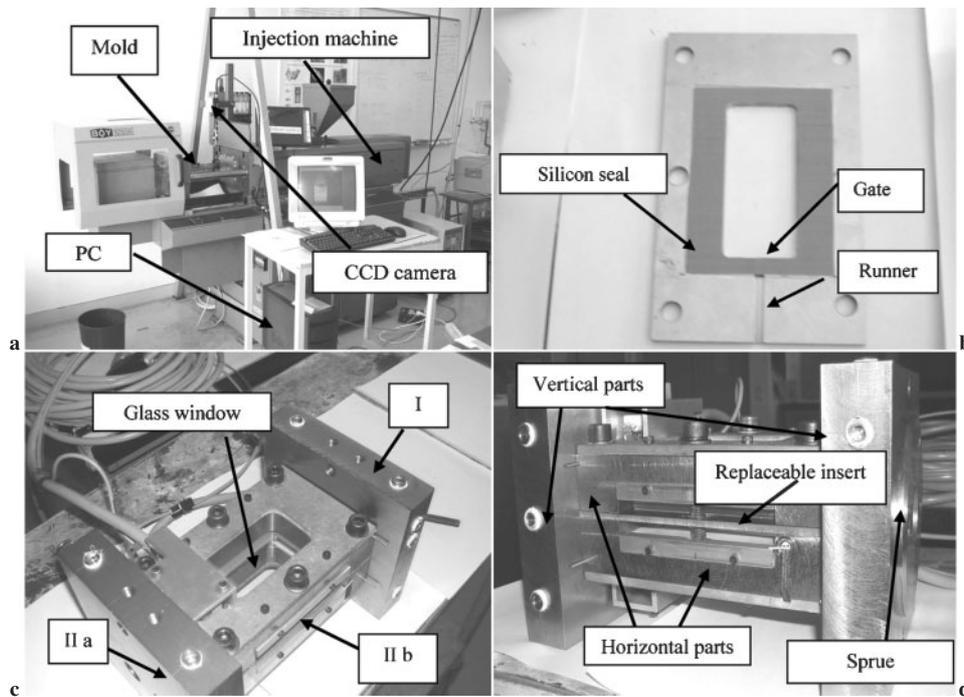
Owing to the risk of jetting is especially high when processing metal injection moulding feedstock, the present study concerns the analysis of this phenomenon using the experimental equipment setup in the laboratory and mainly focuses on the effects of runner size and length that were not investigated deeply so far.

Piccirillo *et al.*^{8,9} investigated the influence of the cross section of gate and geometry of the die cavity on jetting. They concluded that two types of jetting, conventional and solid phase, could be recognised. Jetting refers to the phenomenon occurring when the melt does not form a stable front flow, but rather proceeds as a fingerlike stream maintaining the geometry of the gate as it enters the die cavity.^{8,9} For conventional jetting, a single liquid flow stream moves to the far face of the cavity and then flow upon reversely, resulting in a front flow which fills the cavity backwards. In the case of solid phase jetting, one solid finger flow stream piles up upon itself instead of forming a backward flow front.^{8,9} Both jetting types can result in defects for the final component. The jetting investigations proposed in that paper extend the analysis of jetting previously performed and mainly focus on the effects of the runner length and size.

EXPERIMENTS

Mould and die cavity

The experimental equipments that we are using in the laboratory are as follows.^{4,6,7} Experiments are performed on a Boy 22 M/D injection moulding machine with injection hydraulic pressure control. The maximum injection and carriage pressure control is 160 bars with a maximum injection stroke of 80 mm. The machine has a



a experimental equipment; *b* replaceable insert; *c* mould: upper view; *d* mould: side view

1 Experimental testing equipment and view of mould used in experiments

maximum clamping force of 22 tons, and is equipped with a 22 mm reciprocating screw diameter.

A mould specially designed, has been manufactured and instrumented in our laboratory to perform the injection moulding experiments, especially the investigation of melt behaviour inside the die cavity. The primary feature of the experiments is related to flow visualisation capabilities in real time. This specially adopted mould is divided into three parts (Fig. 1). One vertical block (I) is bolted onto the injection side. The second block (II) that is bolted onto the closing side of the injection machine, is divided into two parts: horizontal block (IIa) fixed onto the closing side, and connected to the horizontal part supporting the glass windows (IIb). Both parts (IIa and IIb) are connected together and bolted onto the closing side. Vertical parts are equipped with cooling channels filled by water in the proposed applications. The horizontal part of the mould is designed as follows to observe the flows of the melt: two glass plates are placed on the upper and lower parts of the replaceable inserts to enable the observation in real time of the phenomena inside the die cavity during the injection process. Between two metallic blocks, a replaceable insert is held with six bolts, and can be easily replaced to change the die cavity shape. This steel replaceable insert is positioned between the glass plates when the mould is closed. This permits the lighting of the cavity through one half of the mould and viewing through the other half. All contact surfaces between metal and glass were coated with a silicon seal to prevent pressure concentrations on the glass plates. The melt enters the die cavity from a conventional sprue,

runner and gate arrangement. During the injection course, shots are realised with various processing conditions for a total cycle corresponding to 0.18 s, the front position is photographed with a frequency corresponding to 25 frames S^{-1} . Only a few selected sequences have been considered in this paper.

Blocks are equipped with six heating cylindrical cartridges powered at 200 W per cartridge, which provides an even temperature distribution. The tests show that temperature distribution is uniformly distributed. The heating temperature control is performed with two thermocouples in the heating zone. The insert cavity is independent of the frame itself and must be manually disassembled after each shot to allow sample ejecting and cleaning. The full mould device completed with all sections is shown in Fig. 1. One use replaceable inserts to perform the experiments.

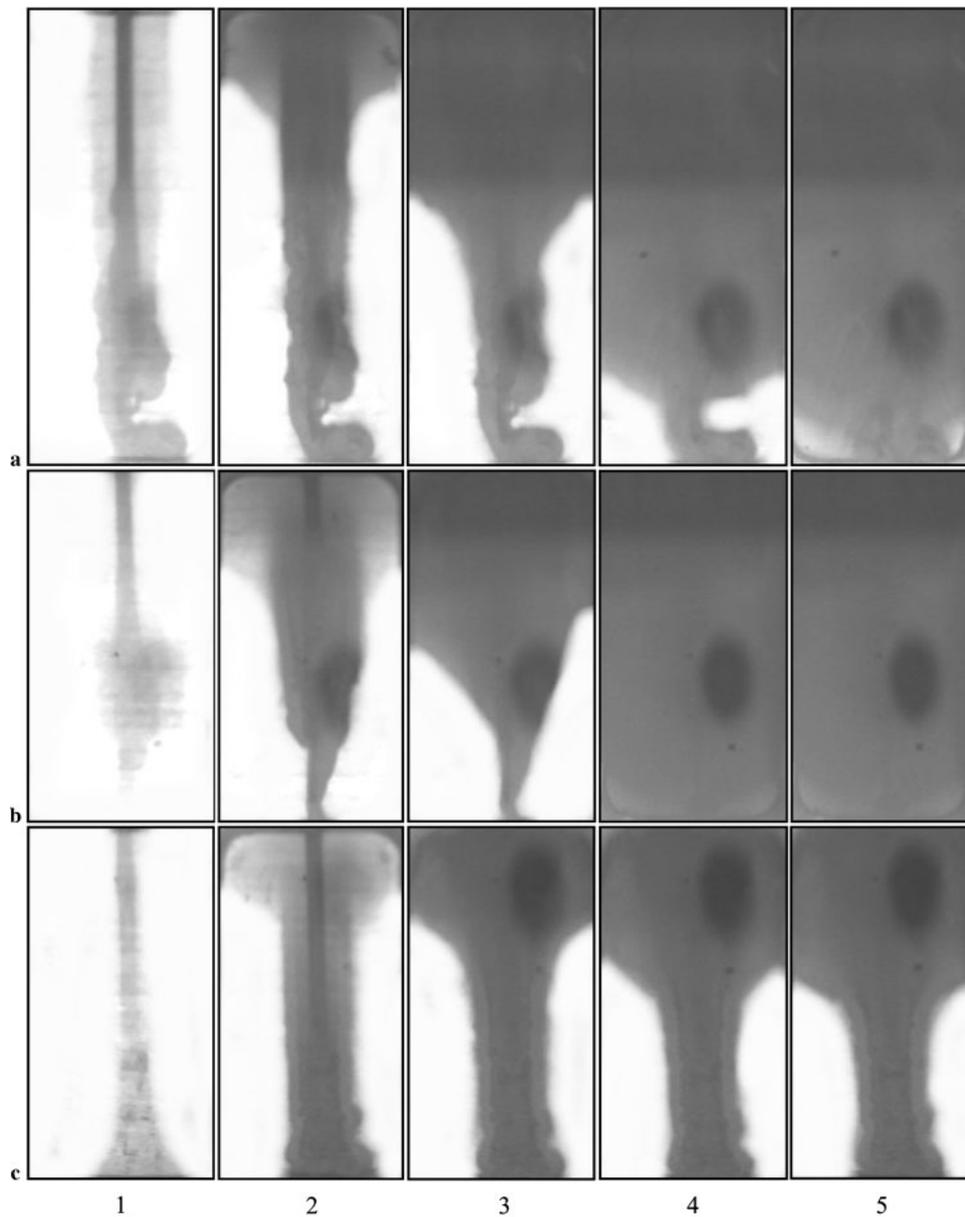
The size of die cavity insert A is $26 \times 65 \times 4$ mm, and the size of die cavity inserts B, C, D, E and F is $26 \times 50 \times 4$ mm (see Table 1). These dimensions were chosen to reproduce experimental conditions corresponding to those given in literature^{8,9} and to produce large components. The runner is located in the middle of the mould component and upper side of frames (see Figs. 2 and 3).

Injection moulding conditions

The feedstock used in the experiments is based on a 316L stainless steel with thermal debinding and is provided by Advanced Metalworking.¹¹⁻¹³ The injection parameters that have been used to describe the components are shown

Table 1 Geometrical characteristics of runners and die cavities corresponding to cases A, B and C

Case of injection frame sequence	Runner length, mm	Runner diameter, mm	Die cavity dimensions, mm
A	45	2	$26 \times 65 \times 4$
B	60	2	$26 \times 50 \times 4$
C	80	2	$26 \times 50 \times 4$
D	45	4	$26 \times 50 \times 4$
E	60	4	$26 \times 50 \times 4$
F	80	4	$26 \times 50 \times 4$



a case A; *b* case B; *c* case C

2 Projected areas of filling stage for runner with 2 mm diameter

in Table 2. These parameters are in accordance to the recommendations from the feedstock manufacturer.

The values for the injection time are set up on the injection machine monitor and the accuracy is correct.

A melt temperature around 200°C is measured in the nozzle and 185°C near the hopper, the same temperature profiles were kept for each shot.

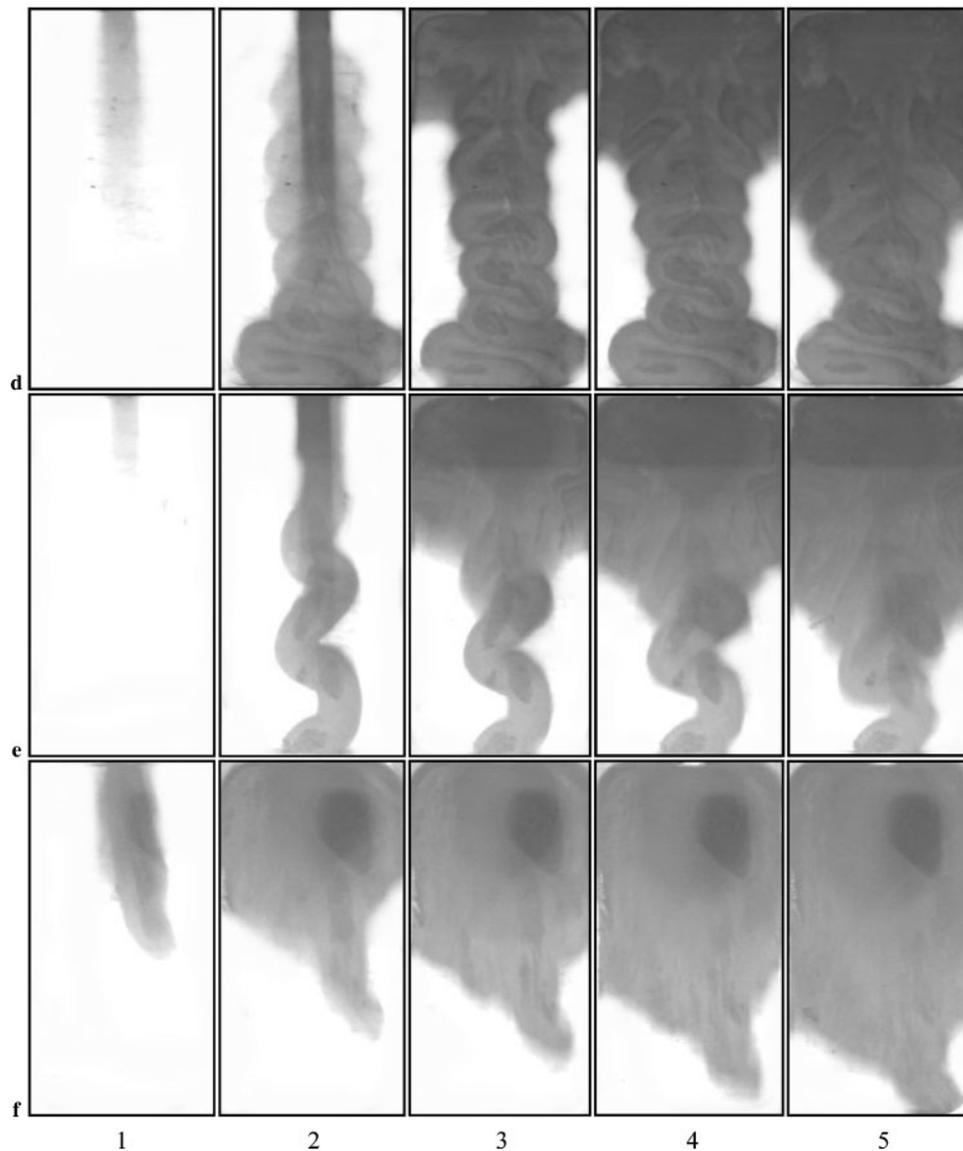
RESULTS AND DISCUSSION

The flow of powder binder melting into the die cavity is not always uniform. When the gate is relatively small and/or the injection speed is too high, a jetting phenomenon appears.^{8,9} This jet is spiralled and kinked in appearance.

The experimental results are summarised in Figs. 2 and 3, representing five frame sequences out of six, which

Table 2 Processing parameters used in comparison with parameters provided by feedstock supplier

Parameters	Injection in cases A, B, C, D, E, F	Values from feedstock supplier ¹¹⁻¹³	Values used in our lab. ^{3-7,10,14}
Injection pressure, bar	160		160
Injection velocity, mm s ⁻¹	160		160
Mould temperature, °C	50	<45	48
Melt temperature, °C	200-185	170-175	165-175
Packing pressure, bar	45	60	60
Injection time, s	0.18	<1	1



d case D; *e* case E; *f* case F

3 Projected areas of filling stage for runner with 4 mm diameter

correspond to photograph series from A to F. Photograph series A shows that the melt enters the cavity in one straight filament continuing through the injection, then the melt buckles and displaces in the die cavity.

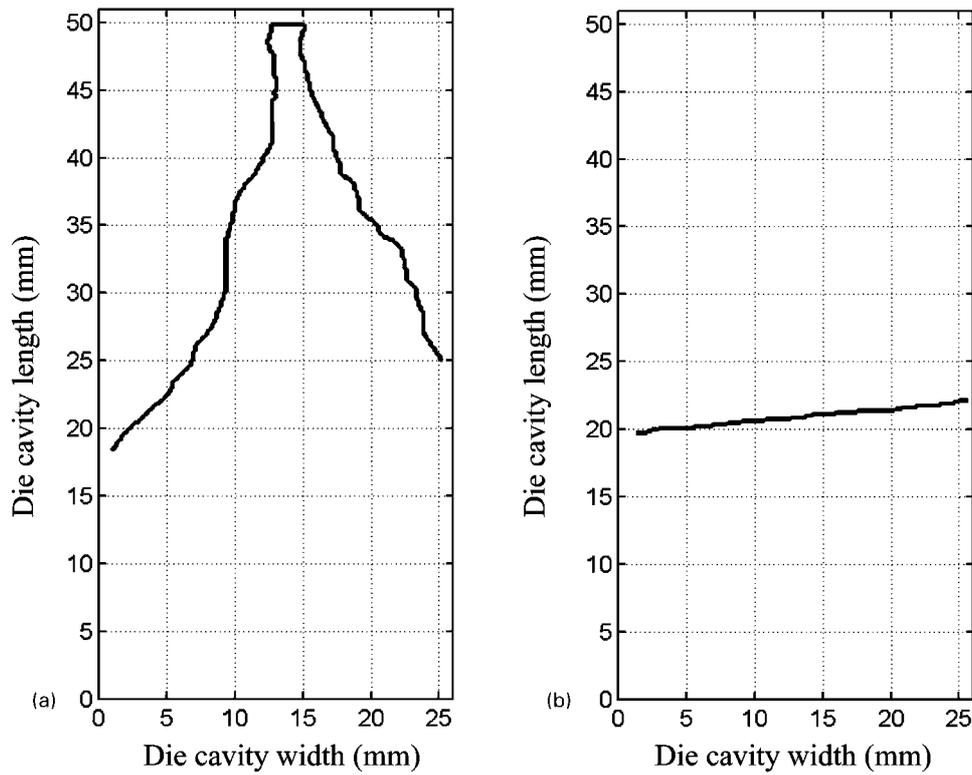
Examples A–C are related to a circular cylindrical gate with a diameter of 2 mm, when comparing the related figures, it is clearly shown that the filling processes are very similar. The melt jet enters the die cavity as a single stream, and reaches the bottom side of the die cavity; the stream is buckled and kinked in a very narrow strip. This strip (made of melt stream) generates a natural barrier against flow and subsequently the die cavity is filled from the upper side. Filling then proceeds in a more common manner because the melt is already in the die cavity. If the filling front goes on too slowly, the jet could have a tendency to cool quickly against the mould walls and incomplete weld lines appear at the junction with the incoming melt. This leads to a rather characteristic surface and internal defects that could be correlated with injection rate and runner geometry. As the filling phase is shortened by decreasing the length of runner, the melt is being filled in the die cavity sooner, and the related phenomena disappears.

In case A, the length of the cavity is 65 mm while in cases B and C cavity length of 50 mm is used, which does not

affect the filling development. In all events, melt stream comes into contact with the bottom of the die cavity and after the filling phase, continues similarly.

Owing to the runner length in case C (80 mm), die cavity filling time is longer than those in cases A and B.

In cases D–F, a circular gate with a diameter of 4 mm is used. The filling stages in case D are similar to those of series A–C. The jet enters in the cavity as a single stream, reaches the bottom side and then the stream is buckled and kinked into a very narrow strip. This strip generates natural barrier against the mixture flow and the cavity is filled from the upper side, then filling proceeds in a more conventional manner, as the melt is already in the cavity. In case E, single stream is observed to be buckled with shorter runner length when compared with cases A–C after it reaches the bottom of the mould cavity. This is probably attributed to the fact that natural barrier associated to the mixture initiates uniform filling from upper side with a buckled strip in the middle. Case F has the longest runner, the melt after leaving the gate largely expands in width in the die cavity, as a result, the stream does not reach the bottom of the die cavity, and when it is approximately in the middle of die cavity, it performs as a barrier resulting in a uniform filling. Therefore, die cavity of case F is filled faster than cases E and D.



a boundary of filled area; b boundary of smart area

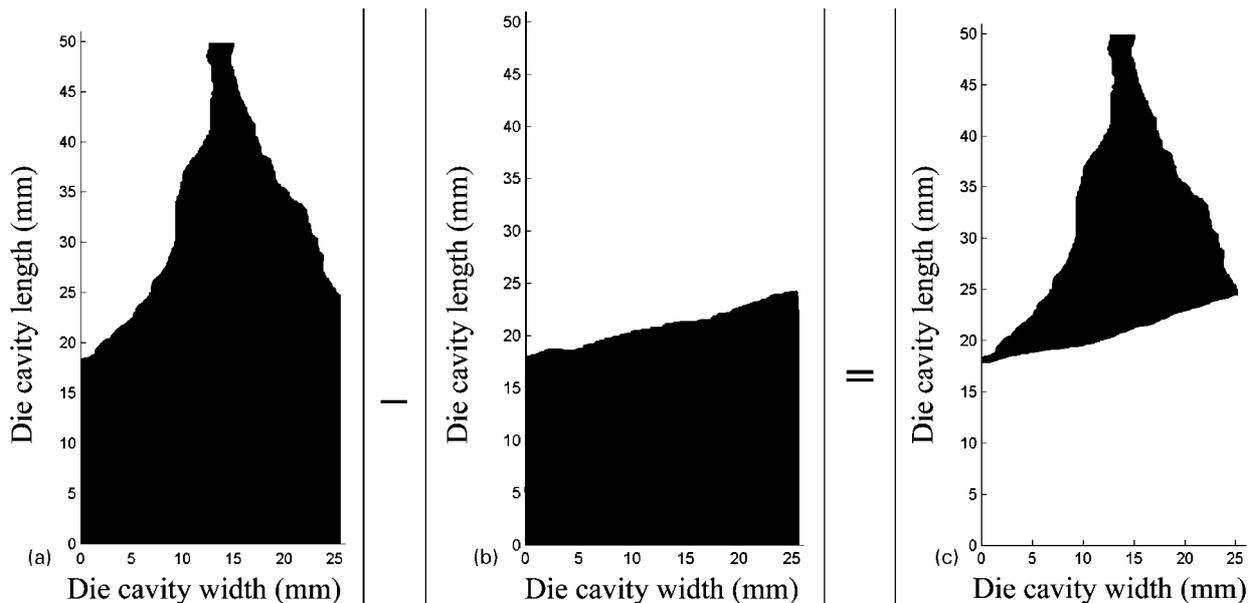
4 Determination of front location for filled and smart areas of case B3

Some criteria have been introduced in order to quantitatively describe these phenomena and provide reasonable interpretations of the previous experimental data. In order to provide criteria for jetting investigations, it has been decided to split the area covered with the stream and mixture during injection moulding into two parts. The smart area is that from the bottom of the mould to the boundary near the upper side of the cavity (Fig. 4). The filled area is the part of the mould that is filled with the mixture containing the stream

(Fig. 4). So the jetting area is from the part between the upper boundaries of the two areas (Fig. 5).

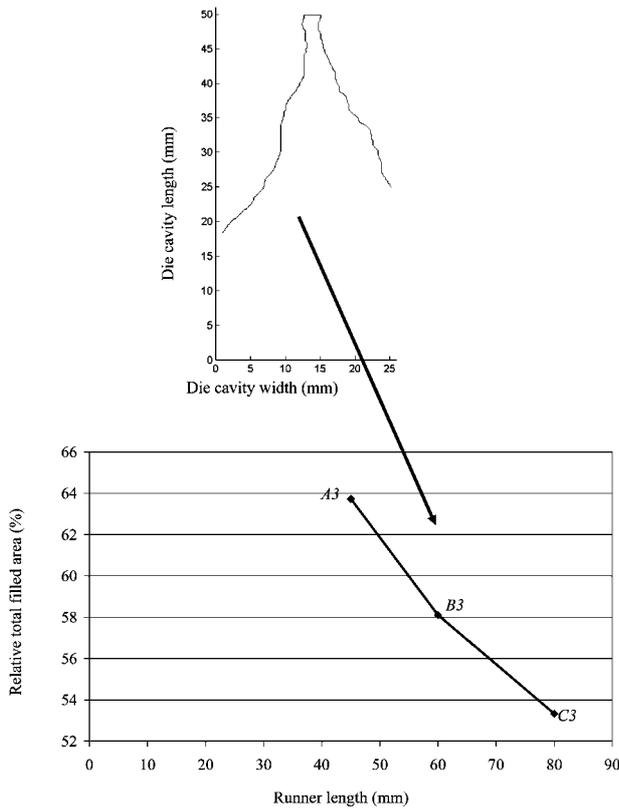
Both areas were defined as areas under the curve which is the boundary of the melt inside the die cavity. A commercial software Matlab[®] was employed to obtain the results, corresponding to different injection cases A3 to B3, see Table 3.

There are numerical coefficients that can be used to draw jetting tendencies graphics during metal injection moulding. It then becomes possible to use these relative values to draw



a filled area, mm²; b smart area, mm²; c jetting area

5 Determination of filled area, smart and jetting areas and relative areas of case B3. $S=L \times l$; L , die cavity length (mm); l , die cavity width; S , die cavity area (mm²). Relative filled area=relative total filled area/ S ; relative smart area=relative total smart area/ S ; relative jetting area=relative total jetting area/ S



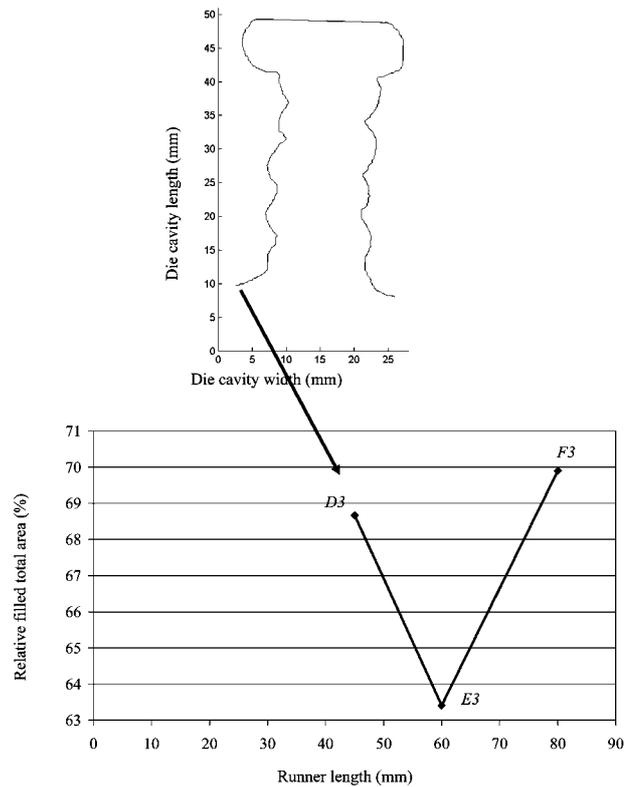
6 Relative filled area versus length of runner with diameter of 2 mm

jetting tendencies with graph analysis. This analysis based on the assumption that the relative areas corresponding to a given mould filling stage can be used as an indicator for jetting characterisation.

In Fig. 6, the relationship between the filled area and runner length is described. For the runner with the diameter of 2 mm, the filled area is smaller when runner is longer. This well agrees with basic experiences in injection moulding because it is more difficult to fill a die cavity with a longer runner.

Figure 7 shows the relationship between total filled area and length of the runner 4 mm in diameter. The median value of 60 mm for the runner length is adopted to predict slightly growing trend, which could be caused by the delay of recording filling stage. It is estimated that the reality should be between E3 and E4 values (Fig. 3), as the corresponding point moves up and the related tendency can be estimated to be going up.

Figure 8 indicates decreasing smart area vs runner length. It can be concluded that the influence of longer cavity on jetting is very important. It can be estimated that smart area is a little shorter than the runner length indicating that longer runner results in increasing jetting and difficulties in filling the die cavity. This is valid for the cavity, when $d/h=2/4=1/2$, where d is runner diameter (mm) and h stands for die cavity thickness (mm).



7 Relative filled area versus length of runner with diameter of 4 mm

From Fig. 9, it can be concluded that longer runner results in the decrease of jetting (larger smart area). This is valid for the cavity when $d/h=4/4=1$, and this results is in fully agreement with studies of Piccirillo and coworkers,^{8,9} in which it is discussed that if $d/h=1$, conventional jetting does not occur. It has been detected that less jetting occurs when $d/h=1$. In contrast, when $d/h=1/2$, jetting increases with runner length. When $d/h=2/4=1/2$, jetting increases with a longer runner length.

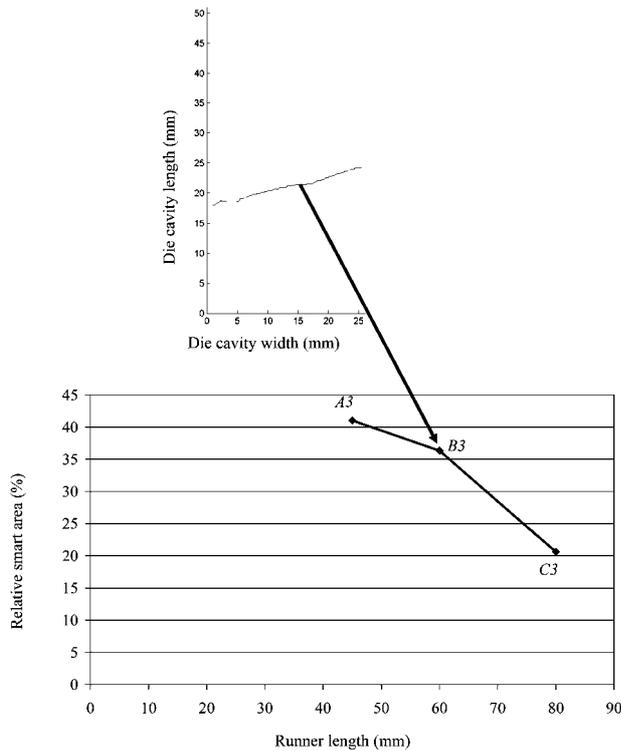
The results obtained from frame analysis of die cavity filling confirms some previously related remarks for powder injection moulding.^{8,9} One study of frame series reported an injection shot which shows that the melt enters in to the cavity in one straight jet filament. As the injection cycle continues, the melt buckles and moves to the bottom of the mould cavity. In the case of conventional jetting, a single liquid flow stream moves to the opposite mould face and then flow upon reversely forming a front flow which fills the cavity backward.

It is mentioned that in case F (the longest runner with a 4 mm gate diameter), the stream does not reach the opposite die cavity wall. It reaches approximately a distance equal to half of the size of the die cavity and then the cavity is uniformly filled.

The development of filling depends on temperature of the melt, injection velocity and gate geometry, welding lines could arise in some areas where melt buckle.

Table 3 Values of relative filled area, smart area and jetting area in accordance with filling sequence

Single frame	Relative filled area, mm ²	Relative smart area, mm ²	Relative jetting area, mm ²
A3	63.73	41.09	22.72
B3	58.11	36.32	21.79
C3	53.33	20.59	32.73
D3	68.66	19.10	49.56
E3	63.41	40.87	22.53
F3	69.90	55.55	14.35



8 Relative smart area versus length of runner with diameter of 2 mm

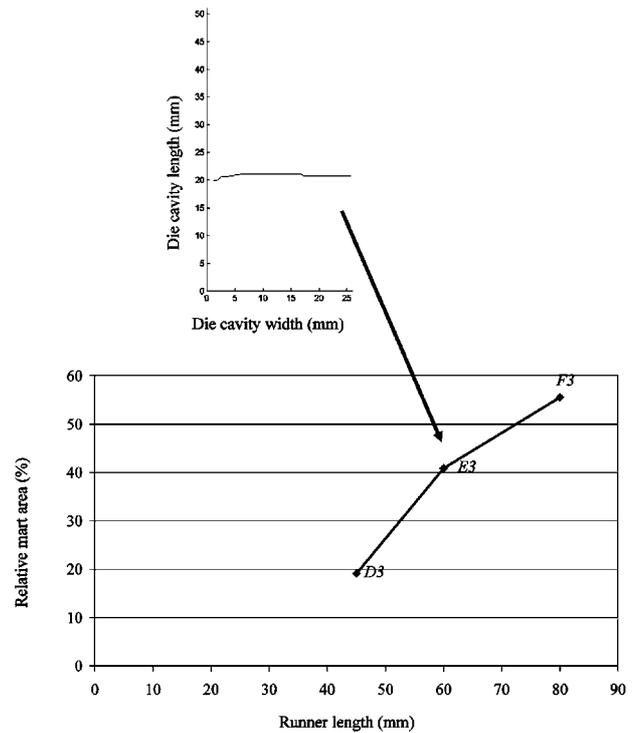
It is noticed that some last readable frames are due to imperfection of light terms and running injection process too fast, the black spot approximately in the middle is a reflection of the camera lens.

CONCLUSIONS

The melt die cavity filling has been examined with respect to various runners and die cavity geometries. The filling process has been characterised with consecutive frames taken during the filling stage by a CCD camera and transparent cavity sides.

The first conclusion resulting from the experiments is that jetting occurs frequently during the filling stage resulting in defects in the injected part. The effect of the runner length has been demonstrated and is mainly related to the size of the mould cavity as well as processing conditions. The obtained results are in agreement with previous ones but are concentrated on the influence of runner length. The experimental monitoring and recording of the injection stage is a valuable investigation to understand and explain the origin of the jetting phenomenon.

Even though the mould die cavity shape that is employed in the analysis has far from complex geometries that can be used in industrial application, it permits setting up the rules to avoid jetting vs mould die cavity geometry as well as processing conditions.



9 Relative smart area versus length of runner with diameter of 4 mm

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