

COMPONENT AND DIE DESIGN PRINCIPLES AND PROCESS PARAMETERS FOR THE METAL INJECTION MOULDING OF A TI ALLOY

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ABSTRACT

Metal injection moulding (MIM) offers advantages for mass production of components over conventional production methods for parts with complex shapes and large production runs. The MIM process includes mixing a fine metallic powder with a polymeric binder to produce a homogeneous feedstock. This enables the production of metallic components in a similar manner to plastic injection moulding. After undergoing a process of binder removal the components undergo a conventional sintering cycle. As significant shrinkage occurs (as much as 30%) this must be considered when designing the die cavity. This paper describes the design and manufacture of a die to produce tensile specimens. Extensive injection moulding trials to produce acceptable tensile components were undertaken. The complexities and possible implications of the design of a mould on the process are discussed.

The outcomes of this research will be used by the CSIR for further development and application of the MIM technology for manufacture of high value components, such as dental implants.

Keywords: metal injection moulding, binder, metal powder, de-binding, shrinkage, sintering

1. INTRODUCTION

Metal injection moulding (MIM) is the process in which a fine metal powder, typically in the sub 20 μ m range, is mixed with a polymer-based compound, called the binder system, and then pelletised to form the feedstock. This is then injected into a mould cavity using a die injection machine very similar to those used in plastic injection moulding. The binder is then removed using a chemical and/or thermal process. The parts are then sintered to achieve maximum density (>90% theoretical) and their final dimensions (shrinkage can be as high as 30%).

A schematic view of the MIM process is shown in Figure 1.

[1] MIM has filled a gap in traditional metal product manufacturing methods. Common metal processing methods fall into 3 categories, each with their own benefits and drawbacks. Standard wrought material removal machining practices, whether automatic, numerically controlled or discrete, are useful

for parts that are either high volume/relative low part complexity or low volume/relatively high part complexity. For high volume production runs, with limited part complexity, pressed and sintered operations are used. With more complex designs, investment castings are often used, the drawback being the prohibitive process cost and time consumed with the handling of one-off use of investment cast moulds in higher part quantities. MIM becomes more advantageous where the volume of parts is relatively high (typically +10,000 parts) with complex, difficult to machine geometries. MIM produced parts are relatively small in size due to the relative high cost of a specific metal alloy feedstock when compared with the wrought counterpart. The larger the part the more material cost plays into the equation, making MIM a less than optimal financial option. The majority of MIM parts weigh 100g or less.

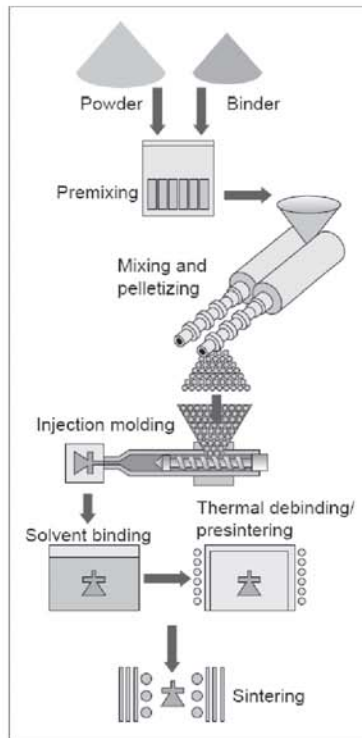


Figure 1: Schematic view of MIM process [1]

2. MOULD DESIGN

In order to characterise the injection moulding process as well as the component properties, a mould to produce a miniature tensile specimen was designed. The geometry of this is shown in Figure 2.

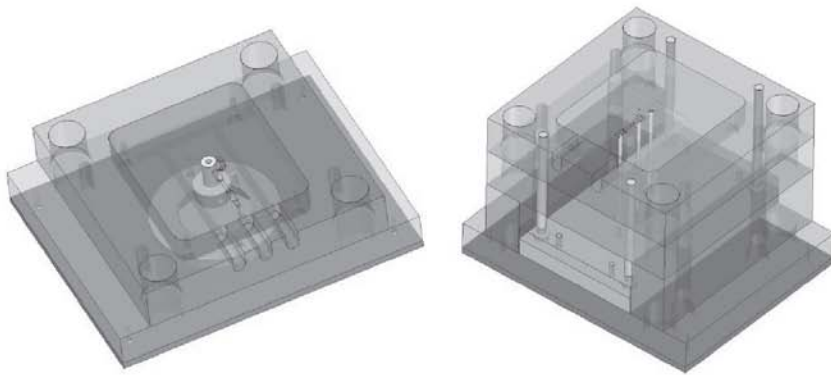


Figure 2: Schematic view of the design of the specimen mould

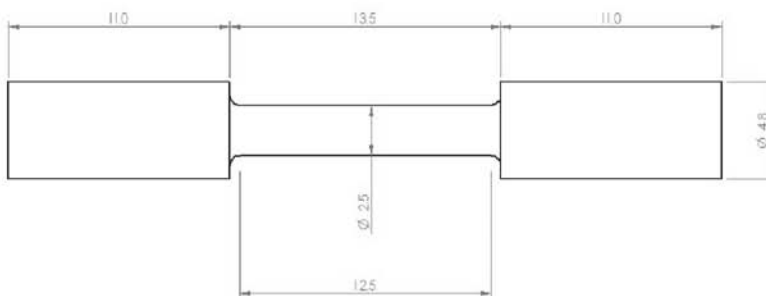


Figure 3: Dimensioned tensile specimen

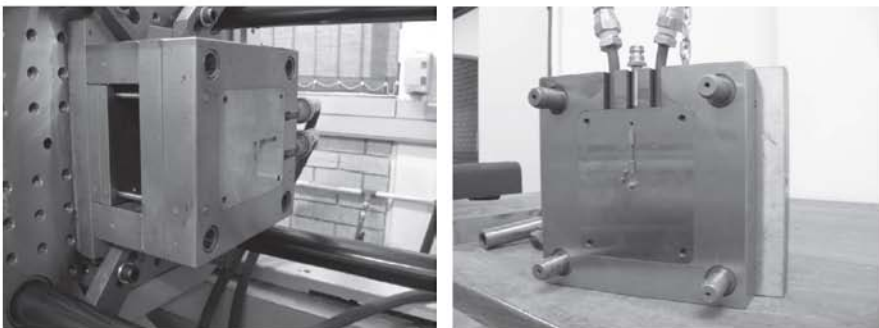
When designing a mould the efficiency and effectiveness of the process must be anticipated and provided for. A number of factors were taken into account and rules based on best practice and experiences [3] were applied to the design, namely:

- **Gate Location:** Material needs to flow into the mould cavity through a gate. This ideally will be located somewhere on the thickest section of the part and will allow the material to flow unhindered into the rest of the cavity. Gates that are directly opposite walls or cores can result in stress concentrations in the material, which can lead to voids, sinks and flow/witness lines.
- Due consideration to be taken regarding gate vestige that will remain on the part. Ensure that it can be trimmed off in the green state or machined off after sintering if necessary.
- Short and thick runner.
- **Eject ability:** Draft must be incorporated into the part cavity, typically greater than 0.5° and must be located on the part normal to the parting line.

- **Material Flow:** As is standard in any type of fluid flow, sharp corners and edges should be avoided where possible.
- **Notches** can be incorporated where 90° angles need to be maintained. A minimum radius of 0.1mm should be applicable on all corners and edges.
- **Parts** should be preferably designed with uniform wall thickness (minimum thickness of $\approx 0.8\text{mm}$). However, if wall thickness must vary, a gradual transition is desirable.
- **Venting:** Release or escape of trapped air in the cavity must be taken into consideration. This is particularly important for reactive metals such as titanium. Therefore, a means to apply a vacuum in the die cavities is essential when injecting titanium alloys feedstock.
- **Mould base:** this is typically made out of pre-hardened tool steel Din1.2312. Cavities are made using through-hardened steel inserts for ease of later modifications.
- **Cooling:** effective cooling is required, independent circuits to be provided on either side of the cavity parting line.

A mould was manufactured following the mould design, specifications and tensile specimen dimensions provided.

Figure 4 below depicts the two halves of the specimen mould.



3. PROCESSING

The feedstock selected was Catamold Ti Al6V4 (BASF) and this has a polyacetal (POM) binder.

The injection moulding was done on an Arburg 270U machine (see Figure 5).



Figure 5: Photo of the MIM Injection moulding machine

The main parameter setting values used on the Arburg 270U were:

Barrel temperature	Zone 1: 160 °C Zone 2: 165 °C Zone 3: 170 °C Nozzle: 175 °C
Mould temperature	125 -127°C, Cooling unit 140°C
Screw speed	Batch1 =30 min ⁻¹ Batch2 =20 min ⁻¹ Batch3 =15 min ⁻¹
Injection speed	10 cm ³ /s
Cushion	5 mm
Moulding pressure	900 bar
Holding pressure	900 bar
Holding time	3 s
Back pressure	0 bar
Cooling time	17 s



Figure 6: Photograph of the green specimen and feeding system

4. RESULTS

Three sets of trials were conducted.

- i. The first trial highlighted some shortcomings on the mould design and manufacture and processing parameters which made producing full shots impossible. The gate size was too small and mould temperatures set too low, which resulted in premature freezing prior to melt introduction in the cavity.
- ii. The second trial yielded better results and some shots were performed. The major problem experienced was related to the shot getting stuck on the wrong side of the mould, i.e. fixed side of the mould.
- iii. The third trial was the most successful. It was possible to produce shots in a semi automatic mode.

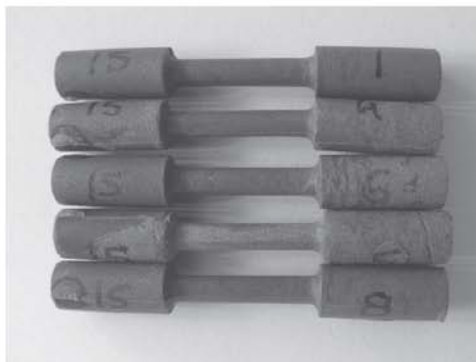


Figure 7: Photograph of the green specimens

The acetal (POM) copolymer, used for the binder, melts at about 160°C and flows quite easily over long flow paths allowing moulding of thin-wall

components. The recommended gate area is equivalent to a circumference with the same diameter as the part thickness. The prescribed feedstock processing temperature is 185°C and care needs to be taken to avoid overheating (above 220°C) as this leads to discolouration and decomposition to form toxic formaldehyde gas. Also the resultant build-up of gas pressure could be potentially dangerous and harmful to both equipment and operators. In fact gas formation and degradation was seen to occur above 175°C.

A further complication is the reactivity of titanium and so tight control on the processing temperature is essential.

The tensile specimens produced were removed from their gating and their weight and dimensions measured (see Figure 8). The results are given in Table 1.

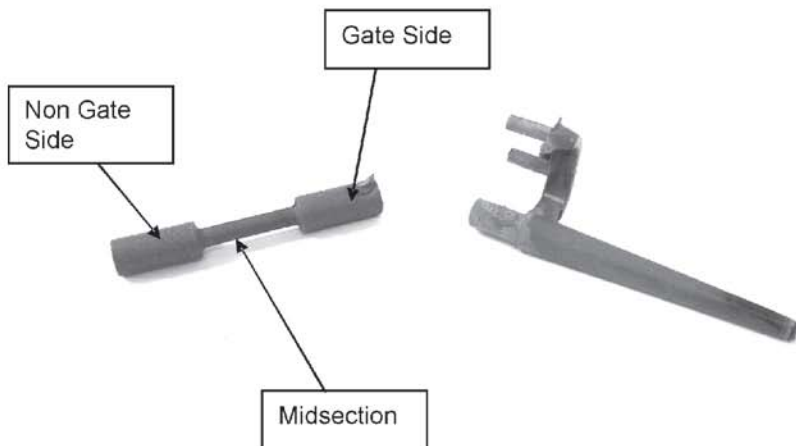


Figure 8: Representation of the separated specimen and runner system

Table 1: Batch averaged weights, dimensions and shrinkage factors

Sample Id	Specimen weight (g)	Gateside diameter (mm)	Non gateside diameter (mm)	Midsection diameter (mm)	Total specimen length (mm)	Gateside length (mm)	Midsection length (mm)	Non gateside length (mm)	Midsection calculated (mm)
Drawing		4.8	4.8	2.5	35.5	11	13.5	11	13.5
In Mould		4.74 to 4.84	4.74 to 4.83	2.45 to 2.58	35.50 to 35.52	10.96 to 11.2	13.1 to 13.3	11.01 to 11.30	
Green Samples									
Batch 1	1.46	4.75	4.74	2.42	35.39	11.12	13.26	11.16	13.12
Batch 2	1.46	4.75	4.71	2.41	35.40	11.12	13.28	11.16	13.12
Batch 3	1.45	4.73	4.70	2.42	35.36	11.15	13.26	11.20	13.01
Sintered Samples									
Batch 1	1.26	4.16	4.17	2.14	30.86	9.77	11.36	9.76	11.32
Batch 2	1.26	4.16	4.13	2.11	30.97	9.74	11.59	9.74	11.48
Batch 3	1.25	4.15	4.15	2.13	30.88	9.73	11.51	9.70	11.45
% Mould shrinkage batch1		15.38	15.10	16.82	15.04	12.59	18.83	12.70	19.26
% Mould shrinkage batch2		15.38	16.22	18.48	14.63	12.94	16.48	12.94	17.60
% Mould shrinkage batch3		15.66	15.66	17.37	14.96	13.05	17.29	13.40	17.90

Shrinkage trend analysis clearly shows that component design should avoid sudden changes in thickness occurring. Notice that shrinkage variation at the thicker section (4.8mm) varies within a range of 1.12% with a medium value of 15.66% and longitudinal dimension (11mm) across the said thickness varies within a range of 0.8% with a medium value of 13%. On the other hand thinner section (2.5) varies 1.66% with average 17.65%.

As the required method of de-binding (using gaseous nitric acid) was not currently available, these samples were then sent to BASF Germany for final de-binding and sintering.



Figure 9: Sintered specimens

The fully processed specimens were dimensioned and weighed to determine the degree of shrinkage and distortion and the results are summarised in Table 1.

5. CONCLUSIONS

The following observations were made:

- i. The feedstock was found to exhibit higher thermal conductivity and higher viscosity than the pure acetal polymer used for the binder.
- ii. The quality of the injected moulded components was dependent on the following parameters:
 - Temperature difference between the mould, melt and barrel must be within $\pm 3^{\circ}\text{C}$.
 - Time for injection must be between 0.5 and 1 second.
 - The hold pressure should be around 2-6 seconds.
 - The cooling time (seconds) is estimated from the formula:
thickness (mm)²

- Pressure applied during injection and holding stages must be around 900MPa or less if possible; no back pressure to be applied.
 - Speed on injection phase to be as low as possible (small shot volume 5-10 cm³/s) but must not exceed 30cm³/s. Screw feed speed not higher than 30rpm.
- iii. The design of the component is similar to that of thermoplastic injection moulded parts i.e. avoid sudden changes in wall thickness, core out thick sections, use ribs instead of thick walls, avoid sharp corners and use a radius of at least 0.3mm.
- iv. Higher viscosity implies higher shear rates accompanied by rising heat on the melt, therefore the pressure drop in the gating system should be kept to a minimum. This can be accomplished by:
- keeping runners as short as possible;
 - keeping runner cross section as large as possible;
 - avoiding sharp bends;
 - machining runners on the demoulding side.

On production moulds, make use of hot runners to reduce feedstock wastage and minimise use of cold wells.

- v. The gating used must fulfil the following criteria:
- give uniform cavity filling;
 - be positioned to allow for easy vestige removal;
 - be as large as possible to avoid pressure drop;
 - avoid free jetting (direct the melt to a wall or pin.)
- vi. As there is very little shrinkage after cooling, removal of the shot must be aided by the following:
- a minimum draft of 0.5-1° should be provided on all cavity surfaces;
 - all the surfaces should be polished;
 - the ejector area should be large and ejectors placed evenly in order to avoid any possibility of tilting due to shrinkage and surface contact grip.
- vii. Positive air extraction is a must when processing titanium based feed stocks and the use of vacuum venting is recommended.
- viii. The mould temperature is one of the most important parameters. Insulating plates between mould and machine clamping are recommended. Uniform temperature control of the mould cavity must be maintained within $\pm 2^{\circ}\text{C}$. Avoid temperatures above 140°C on the mould areas in contact with the melt.

6. REFERENCES

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