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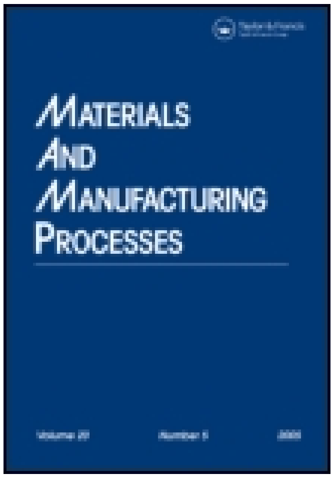

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Process Development and Product Quality of Micro-Metal Powder Injection Molding

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Process Development and Product Quality of Micro-Metal Powder Injection Molding

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Injection molding has been found to be an efficient and cost-effective manufacturing technique for the production of a wide variety of parts and components at both macro- and microscale. This is attributed to the application of robust design and process development. However, every manufacturing technique is challenged by quality issues and part defects, but tackled by continuous improvement framework(s). This systematic monitoring and control approach of dimensional accuracy, mechanical properties, and surface quality of the finished part strongly depend on process conditions at different production stage. Therefore, the aim of this study is to review process development of micro-metal injection molding; focusing on critical factors influencing part quality and optimization of process parameters. The critical factors that influenced the finished part quality are part design, mold design, material selection, machine, and process conditions. Optimizing mold temperature, melt temperature, injection speed, injection pressure, cooling time, packing, and holding parameters improve the quality of the molded part. This trend of process development of injection molding gave rise to a broad scope of applications with brighter future potentials for the next decades, particularly for medical and electronics applications.

Keywords Injection; Micro-metal; Molding; Optimization; Parameters; Process; Product; Quality.

Introduction

The concept of injection molding can be linked to the invention of John and Isaiah Hyatt in the year 1872. They were the first to patent injection molding machine. This machine uses a plunger to inject the plastic melt through a heated barrel into the mold cavity. However, the industry has been progressively developing with a complete turnaround from a plunger type for the first screw injection molding machine in the year 1946 by James Watson Hendry. This design concept dominates the industry today, but further developed into multi-shot and bicomponent injection molding at both macro- and microscale. Meanwhile, exploration of this arising technology is still ongoing by researchers in order to fully develop the process at microscale, considering the effect of processing paramters and powder particle size on feedstock and indeed the finished parts [1–7].

Microfabrication of parts by powder injection molding (PIM) encompasses metal powder injection molding (MIM) and ceramic powder injection molding (CIM). This technology offers significant cost savings, increased design and material flexibility, increased possibility of miniaturization, shape complexity, high mechanical properties, good surface finish, and dimensional accuracy of parts [8–12]. These capabilities gave PIM an edge over other microfabrication techniques such as micromachining, hot pressing, laser ablation, slip/tape casting, etching, and LIGA. Meanwhile, increased micro-miniaturization of mold cavity and part dimensions brought about technical issues, which affect part quality.

The downsize of machine components and or part dimensions to produce miniature products by micro-injection molding results in product defects such as incomplete filling of mold cavity, product deformation in debinding, and sintering process. Similarly, nonhomogeneity or segregation of particles at mixing stage has been a challenge [13–16]. However, these problems were tackled by carefully selecting process parameters and then optimized for the best product quality.

Therefore, this study aims to review research trend over the past one decade and to highlight the process development of micro-metal injection molding (μMIM) and its challenges, with a focus on improvement of product quality through optimizing process conditions, supported by robust design of experiment (DOE) for process parameters to enhance productivity.

Evolution of μMIM process

High market demand of miniature microparts influence the manufacturing of microdevices or systems. This gave rise to the development of microelectromechanical systems (MEMS), micromachines, and or microsystems which have greatly increased in recent times [17–19]. However, the need to balance the increasing demand of these products shifted the attention of both researchers and stakeholders to the development of cost-effective manufacturing techniques, which will enhance product quality and productivity. Nevertheless, these

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characteristics were satisfied by μMIM and found suitable for mass production of complex, intricate shapes and sizes [20–22]. Figure 1 illustrates the evolution of μMIM and finished part production processes.

The μMIM evolves from process integration of powder metallurgy and plastic injection molding technologies [23, 24] at microscale. This technology also undergoes the four processing stages of MIM, which are: mixing (feedstock preparation), injection moulding, debinding and sintering [25–30]. As process development of μMIM inues, researchers support their ideas and innovation from theories of polymer injection molding (IM) and conventional micro-injection molding (μIM). This is to give a clear understanding of μMIM which undergoes the same processing steps.

Mixing

The preparation of injection molding feedstock begins with material selection, followed by mixing of the metal powder and binder in correct proportions known as powder loading. Binder systems of MIM are broadly classified into four categories: these are the thermoplastic based, thermoset based, gelation, and freeze forming [27, 31]. A survey of the literature indicates that the use of thermoplastic-based binder now dominates. Wen et al. [32] reviewed the design and binder formulation for titanium metal injection molding (Ti-MIM) process. Their study gave a detailed discussion on four broad classifications of the binder systems for PIM, covering wax-based, polyoxymethylene-based, aromatics-based, and water-soluble binder systems. In addition, the water-soluble binders are further subgrouped into gelation- and non-gelation-based binder systems. The water-soluble binders have gained acceptance due to the environmental toxicity issues posed by organic solvent (such as *n*-heptane and *n*-hexane) during debinding. However, formulation of the binder systems focuses on the homogeneity of the feedstock as a measure to control defects and ensuring physical and mechanical properties of the finished part [19, 33–35]. This depends on the powder loading of the feedstock design.

According to Liu et al. [36], typical volumetric percentage proportion of binder to form a homogenous feedstock is between 35 and 50 vol.% in a powder mix. This becomes paramount for the fact that optimal powder loading produces the best green part strength. For instance, powder loading of micro-nano stainless steel feedstock is presented in Table 1. In addition, optimal powder loading is required as it reduces part shrinkage and other associated defect. Therefore, this makes mixing a very important process, and error at this stage may be difficult to correct. Therefore, the need for homogenous mix of the feedstock is critical. Meanwhile, researchers depend on the characteristics and rheological properties of the feedstock [19, 37–40]. Suri et al. [41] found out that feedstock properties were influenced by processing parameters such as mixing speed, blade geometry, material feed rate, filling speed, processing temperature, and duration of mixing. In some situations, powder characteristics (particle size and shape, specific surface area) and binder characteristics (binder composition, viscosity) also have an impact on the quality of the feedstock [37, 42–45].

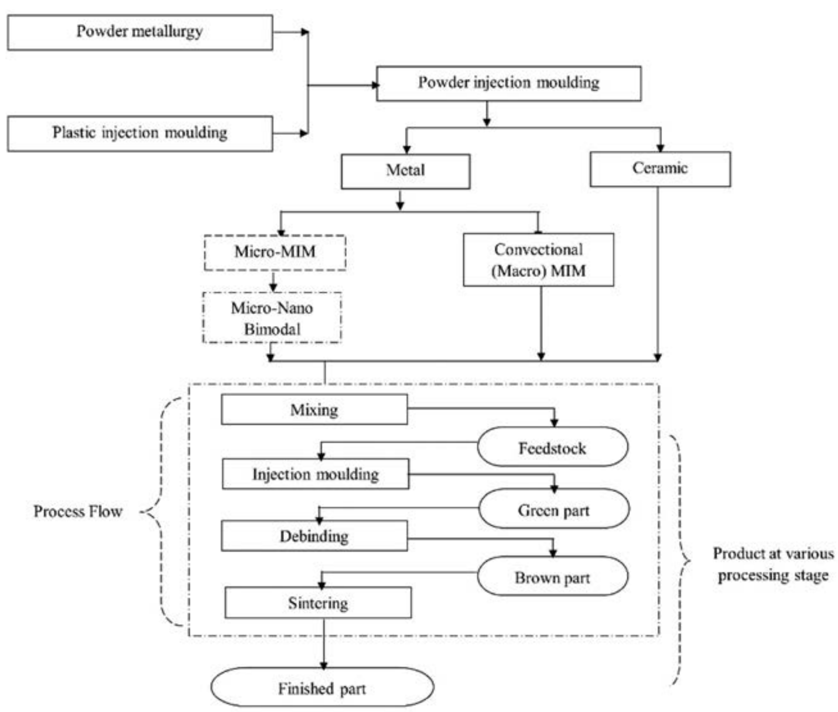

FIGURE 1.—Evolution of μMIM process and product flow.

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TABLE 1.—Powder loading of micro-nano stainless steel feedstock.

Number of loading	Powder loading, vol.%			Reference
	Range	Critical	Optimal	
3	52–57	—	54	[40]
4	60–72	—	68	[46]
5	62–70	68–70	66	[47]
5	62–70	66–68	66	[48]

The quality of finished part depends strongly on feedstock, which is the first product of μMIM. Hossain et al. [49] investigated the mixing parameters and performance characteristics for powder–binder in metal injection molding. Ahn et al. [21] and Supati et al. [40] carried out an extensive investigation on the effect of powder and binder rheological properties. However, an indication from the literature shows that attention was given to particle size distribution [46, 48, 50–52], mold dimensions [39], part geometry [53], and processing condition [54–56] which influence the dimensional accuracy and mechanical properties of the molded part. In addition, researchers now adopt a new design for formulating feedstock, by the introduction of micro-nano powder mixture and low viscosity binder systems for μMIM [48, 57]. The nano-sized powders enhanced the critical powder volume concentration (CPVC) of the micro-metal feedstock from 67.33 to 78.33 vol. % and caused a 40% reduction in injection temperature [58].

Injection Molding

This is the second processing stage whereby the feedstock prepared during mixing is fed into the injection molding machine. This process can be broken down to four phases, which are plasticating/filling, holding and or packing, injection, and cooling phase, respectively. It is observed that researchers used Battenfeld Microsystem 50 and custom-made machine, especially for μIM. According to Giboz et al. [59], μIM process is more than just scaling down of the conventional injection process, but it requires a thourogh rethinking of the entire process. Meanwhile, researchers such as Michaeli et al. [60] and Chang et al. [61] have developed micro-injection molding machine with favorable output in relation to the commercially available types.

However, consistency of parts produced from injection molding machine in terms of part dimension and quality is achieved through process parameters, some of which are speed, time, pressure, and temperature of the barrel, melt, and mold, which have to be monitored, controlled, and optimized [3, 28, 42, 62–66]. These involved the application of optimization techniques to performance characteristics and process parameters [67–70]. This shall be further discussed under optimization. Subsequently, the product at this stage is called "green part," and further process at the next processing stage is called "debinding."

Debinding

This is the third processing stage of the injection molding technique which involves the removal of binder, known as "debinding." At this stage, the product is called "brown part." It is achieved via solvent [29, 71, 72], catalytic [73, 74] or thermal [75–77] processes, or combination of the process. Meanwhile, multistep debinding techniques are employed, optimizing processing conditions (aspect ratio, time, and temperature) as well as solvent medium [33, 78, 79] and then followed by thermal debinding. Thermal debinding is a process whereby the green part is condensed in a furnace [25, 80] but associated with part defects such as crack, slump, porosity, and blister. Figure 2 shows a trend of temperature profile over time, observed during thermal debinding and sintering process.

According to Wongpanit et al. [27], one of the critical issues in MIM technology is how to eliminate defects during thermal debinding. Meanwhile, mechanical properties and other defects such as distortion could be reduced via addition of acrylic acid grafted to the binder content. The kinematic study of the binder components of the feedstock during debinding is paramount. Enneti et al. [75] presented an explicit review on thermal debinding process with details of the master decomposition curves (MDCs). Equation (1) expressed the relationship between the parameters considered:

$$\Phi(\rho) = \theta(t, T) = \int_0^t \frac{1}{T} \exp\left(\frac{-Q}{RT}\right) dt \quad (1)$$

where $\Phi(\rho)$ is the densitification, t is the time, T is the absolute temperature, Q is the apparent activation energy, and R is the gas constant. Meanwhile, to accelerate binder removal and avoiding defect, researchers now prefer solvent extraction method [29].

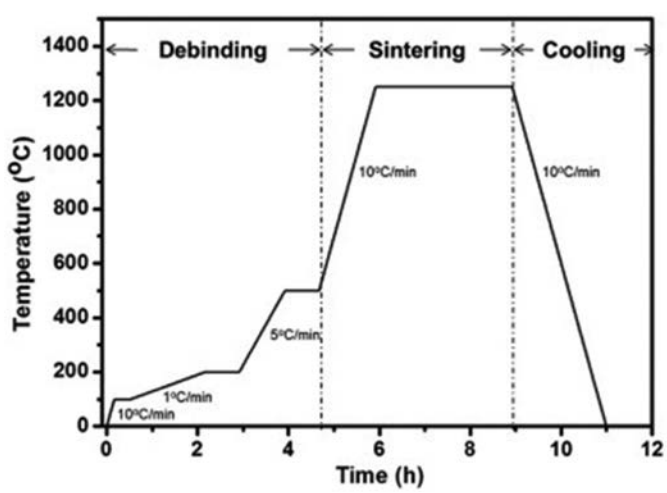

FIGURE 2.—Schematic of the thermal debinding and sintering processes [81].

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Sintering

This is the final stage whereby the brown part is subjected to heat in a thermal furance. This process removes the remaining binder and pores from the brown part and improves the mechanical properties of the finished part [25, 80]. However, the problem of part distortion must be well guided as it remains a challenge which manifests at this stage. Figure 3(a) illustrates the possible flow path of the melt within mold cavity, generating internal stresses due to frozen-in orientation, while Fig. 3(b) depicts distortion of brown part due to stress relaxation.

Heng et al. [82] investigated the effect of sintering temperature range on microstructure and mechanical property of molded parts. Their study revealed that mechanical properties of a sintered part improved with increasing sintering temperature. Similary, Okubo et al. [83] investigated the effect of powder particle size and sintering conditions on dimensional accuracy of micropart produced. However, optimum sintering temperature has to exist to improve the dimensional accuracy while downsizing the particle size. Raza et al. [84] determined the optimum cooling rate of 10°C/min for both the mechanical properties and corrosion resistance of the sintered 316 L stainless steel part, optimizing temperature, time, heating rate, and cooling rate.

Optimization and simulation of injection molding

Part design, mold design, material selection, and machine and process conditions are critical factors that influence the finished part quality in injection molding.

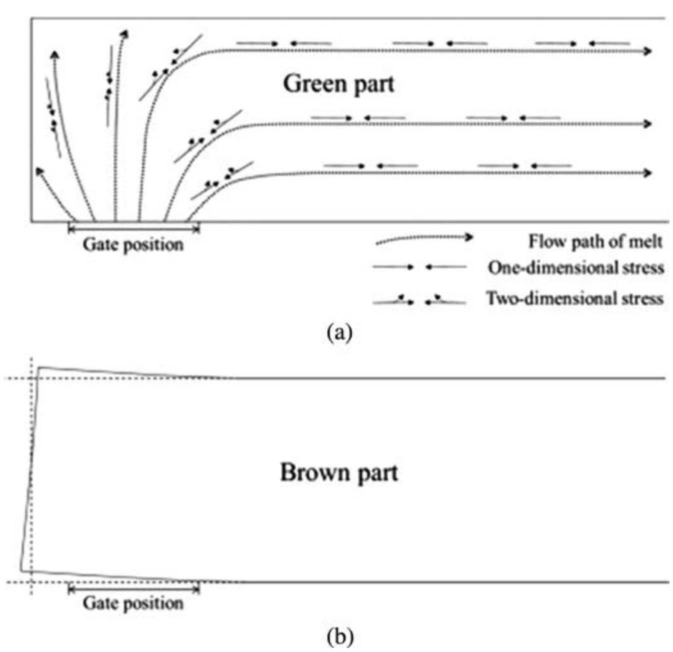

Figure 3.—(a) Possible flow path of melt in mold cavity generating internal stresses because of frozen-in orientation and (b) distortion of brown part due to stress relaxation [27].

These process conditions are selected and controlled for best product quality by the application of optimization techniques. Figure 4 illustrates a broad classification of optimization techniques applied by researchers to injection molding processes. These methods were developed based on statistical, global search process and approximate mathematical functions. Numerical simulations are sometimes employed based on DOE for collecting data on the optimization techniques.

Application of optimization techniques to injection molding by researchers are non-iterative methods [85–90], iterative methods [91–98], and intelligent algorithms [95, 97, 99, 100] as depicted in Figure 4. Meanwhile, sometimes researchers combine these methods or techniques [92, 96, 101–112] to enhance the effectiveness of the method. Research findings from literature show that DOE, optimization techniques, factor interaction, and quality control as well as the critical factors influenced the finished part quality as illustrated in Fig. 5. Annicchiarico and Alcock [113] recently reviewed factors that affect the shrinkage of molded part for both macro- and microscale injection molding. Their study focused on material behaviours, processing parameters, mold design, and specimen design as branches that influence the shrinkage of molded part.

Researchers usually carried out simulation using software and then validated with experimental results. This act has positively affected injection molding output in the last decades [114, 115]. Quite a number of commercial softwares such as ABAQUS, ANSYS CFX®, SIGAMA®, Moldex3D®, Moldflow®, C-Mold®, and others are widely used for injection molding simulations [116]. However, these softwares were developed for macroscopic applications, but found to be useful with some basic assumptions for analysis of models developed at micro/nano scale [66, 117–119]. Classification of simulation-based optimization is shown in Fig. 6.

According to Liu et al. [36], computer simulation have successfully reduced the design-to-manufacture cycle time, through optimization of mold design and process parameters. It is observed from the literatures that investigation were largely on melt temperature, mold temperature, holding pressure, injection pressure, and injection speed to improve part quality [120–123]. Meanwhile, other factors such as material characteristics and powder loading, shot size, cavity geometry, and surface finish of the mold may influence part quality. Thus, it is necessary to apply DOE to optimize process especially during mold filling for better product quality of μIM [67, 124–127]. Attia and Alcock [124] reviewed DOEs used by researchers in evaluating the effect of process paramaters on responses factors and developed a multiple quality criteria for micro-injection molding, but more work is needed especially for μMIM.

In addition, part quality depends on the ability of the feedstock melt to flow into the mold cavity for micro- and nanostructures [118]. Lin et al. [128] examined the effects of the processing parameters on the filling of nanofeatures components through the development of analytical models which were verified experimentally.

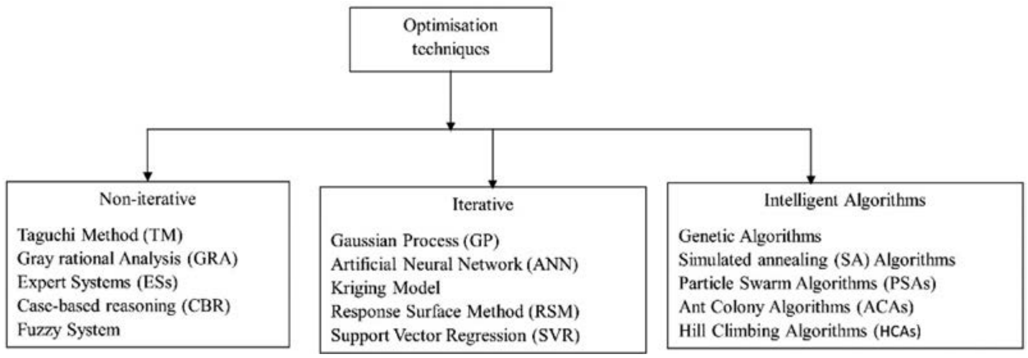

FIGURE 4.—Classification of optimization techniques used for injection molding process.

Their results showed that higher mold temperature was required at nanoscale filling. Meanwhile, whenever the filling aspect ratio is over 1, the mold temperature should be raised near or above the glass transition temperature of the polymer. Meanwhile, the suitability of analytical methods diminishes as the complexity of the MIM increases; this gave rise to the use of numerical methods.

Mathematical formulation and modeling have been implemented by the application of suitable numerical methods in solving the governing equations developed or formulated for injection molding simulation [129–135]. Jiang et al. [136] analyzed the feedstock melt and solid phase considereing basic assumptions of non-Newtonian and non-isothermal fluid flow. The continuity equation (2) and momentum equation (3) of the feedstock melt are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{2}$$

$$\frac{\partial p}{\partial x}=\frac{\partial}{\partial x}\left(\eta\frac{\partial u}{\partial z}\right),\frac{\partial p}{\partial y}=\frac{\partial}{\partial y}\left(\eta\frac{\partial v}{\partial z}\right),\frac{\partial p}{\partial z}=0 \tag{3}$$

From Eq. (2), u, v, and w repressent velocity function along the x, y, and z axis, respectively, while p represents

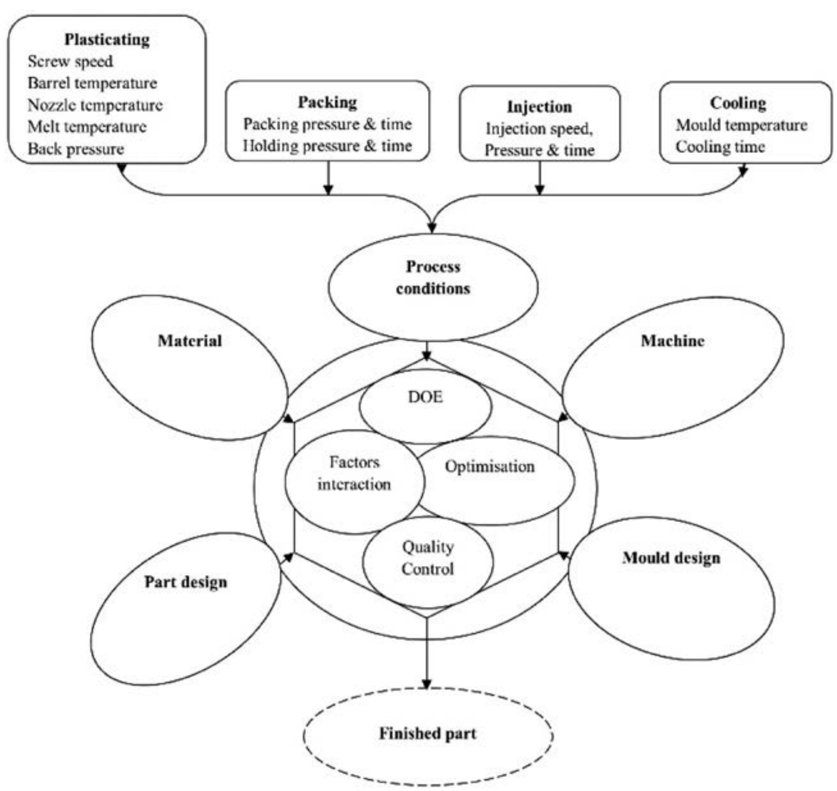

FIGURE 5.—Process parameters and critical factors influencing part quality in injection molding.

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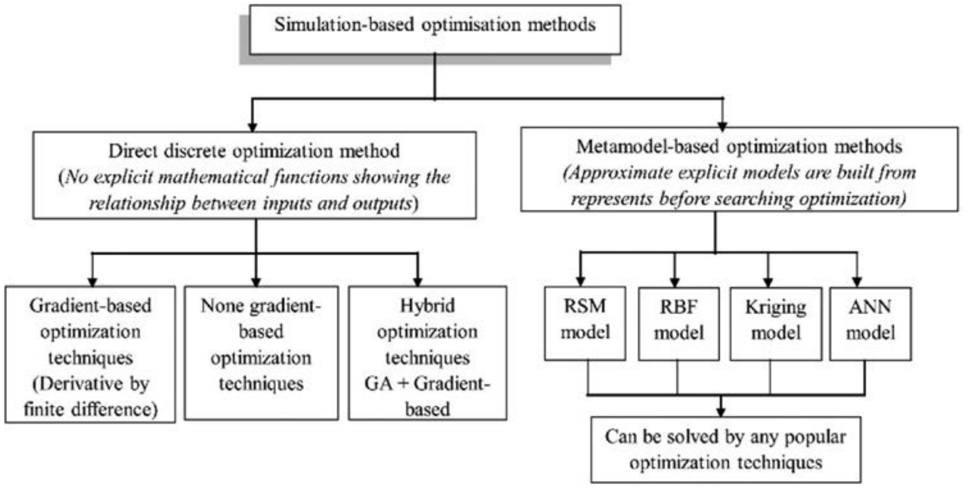

FIGURE 6.—Classification of simulation-based optimization techniques [1].

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the pressure and η is the viscosity. The energy equation of the melt is then expressed as:

$$\rho C_{\mathrm{p}}\left(\frac{\partial T}{\partial t}+V_x\frac{\partial T}{\partial x}+V_y\frac{\partial T}{\partial x}\right)=K\frac{\partial^2 T}{\partial x^2}+\eta\dot{\gamma}^2 \quad (4)$$

In Eq. (4), the shear rate $(\dot{\gamma}^2)$ represents $\left(\frac{\partial v_x}{\partial z}\right)^2+\left(\frac{\partial v_y}{\partial z}\right)^2$, T represents the absolute temperature, t represents the time, ρ represents the melt density, C_{p} represents the specific heat, and K represents thermal conductivity of feedstock. The energy equation for the solid phase is expressed as:

$$\rho_{\mathrm{s}} C_{\mathrm{p_s}}\frac{\partial T_{\mathrm{s}}}{\partial t}=K\frac{\partial^2 T_{\mathrm{s}}}{\partial z_{\mathrm{s}}^2} \quad (5)$$

These governing equations are solved using numerical methods either analytically or implemented by software. However, finite difference method (FDM) and finite element method (FEM) [137–139] methods were used mostly for the analysis of melt flow with variant conditions such as isothermal, non-isothermal [140, 141], and non-Newtonian [140, 142]. Recently, researchers now applied meshfree methods [137, 143–146] to injection molding due to complexity of handling mesh or grid elements in analysis.

PRODUCT FABRICATION AND APPLICATIONS

The drive toward product miniaturization has been greatly on the increase in the past few years. Micro-molding methods such as injection molding, hot embossing, reaction injection molding, injection compression molding, and thermoforming [147–149] were developed for fabrication of microparts. Typical components manufactured by micro-injection molding are broadly categorized into Type A and B. In Type A, the overall size of the part is less than 1 mm and in Type B the component dimension is larger but incorporates micro-feature(s) size which is less than 200 μm [150]. A detailed review on the capabilities of micro-powder injection molding as microfabrication techniques can be found in [9].

Fabrication

It is now possible to fabricate three-dimensional hollow part [151] and movable parts [152] with μMIM. Attia et al. [152] proposed a novel framework to fabricate moving interfaces by powder micro-molding. These developments were facilitated as μPIM proved to be cost-effective manufacturing techniques for production of microdevices and components.

Inspection and Quality Control

The act of checking part specification during manufacturing process is termed inspection. This is usually an aspect of quality control which can be either destructive or nondestructive. Therefore, quality control is a systematic use of quality tools, frameworks, and methods to ensure certain standard or specification for the product. Part quality is influenced by the effective control of the process conditions at different stages [153] and the response factors (quality characteristics) which are dimensional accuracy, mechanical properties, and surface quality of the finished part [42]. Fabrication of molded part quality depends strongly on the critical factors which were illustrated in Fig. 5. The interrelationship between critical factors is elaborated further here with fishbone diagram as shown in Fig. 7. In addition, qualification methods such as pycnometer density, cavity pressure, part dimension, part mass, weight loss, microstructure, and mechanical testing were employed to achieve defect-free parts [154].

Zhao et al. [28] proposed a nondestructive online method for monitoring injection molding processes by collecting and analyzing signals, using electrical sensors installed in the machine. This is a measure to assess the entire molding process and ensure the best quality of the finished part. Also Gasparin et al. [155] investigated the quality of injection molded component, based

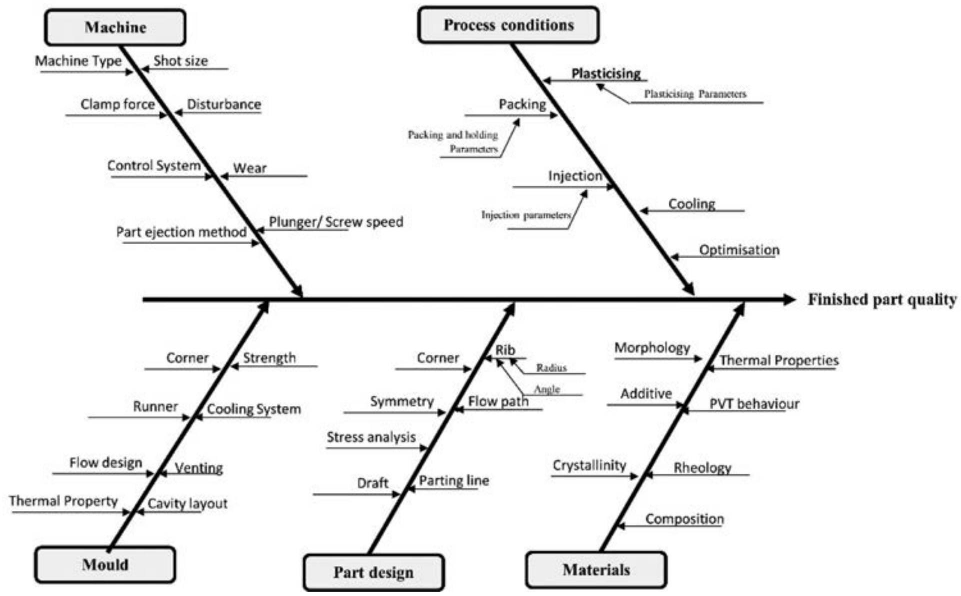

FIGURE 7.—The interactions of critical factors influencing part quality of injection molding products.

on optical coordinate measuring machine. The measurements were analyzed by statistical quality control tools to determine the process parameter which influence the mechanical parts produced.

Applications

The demand and manufacturing of complex, intricate miniature parts and microdevices by MIM has been on the increase. Table 2 presents some major applications. However, a brighter area of application is the microdevices and medical implants [156]. According to German [157], medical applications are growing from an early base of endoscopic devices and will become enormous as MIM becomes widely accepted.

Applications of injection molding to product manufacturing have changed product design significantly across all sectors. Meanwhile, the technique has some challenges just like other manufacturing techniques.

TABLE 2.—Market partition by region and application as percent sales for 2007 [157].

Application	North America	Europe	Asia	ROW
Automotive	30	28	18	0
Consumer	0	32	15	0
Dental	18	14	0	8
Electronics	6	0	41	0
Firearms	6	9	0	66
Hardware	0	0	1	0
Industrial	6	3	14	24
Medical	34	2	2	1
Military	0	1	2	1
Other	0	9	5	1

RESEARCH CHALLENGES AND FUTURE WORKS

Despite achievements and research breakthrough recorded, there are still problems that need attention as they affect the finished part quality. Recently, Annicchiarico and Alcock [113] discover a gap of inadequate information for the evaluation of molded part specimen shrinkage with dimensions less than 10 μm. Likewise, Attia and Alcock [9] observed disparities of design of microparts for μPIM. Indeed, these problems and others have raised concern among researchers for the need of standard priniciple and practicse of μPIM as it affects the finished part quality.

Materials

Material selection has been identified as a critical factor that influences part quality. It direclty affects the strength and shrinkage of the finished part quality. Therefore, the formulation of the feedstock matrix, i.e., the binder constitutes and powder loading, needs to be addressed for the fact that researchers usually report a relatively mean design point of their study as the optimal powder loading of specimen as presented in Table 1.

According to Li et al. [46], it is almost in possible to determine the critical powder loading in practice, but the optimal powder loading lies just slightly below the critical one. Meanwhile, Kong et al. [47] determined critical powder loading using four different approaches. It is, therefore, established from the literature that a feedstock at the optimal powder loading produces the best quality part having good rheological properties during mixing—little shrinkage and warpage with good mechanical properties.

It is then important to study the material properties of the feedstock. The current research trend focused on the

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developmenet of new feedstocks such as aluminium- and copper-based feedstocks as well as the introduction of nanoparticles into the feedstocks. This now drives research to micro-nano and bimodal injection molding, as illustrated in Fig. 1. These materials were selected based on their physical, mechanical, and thermal properties; for instance, aluminium has been selected due to its light weight and relatively high thermal conductivity which are required in the development of heat sinks for electronics application. Likewise, research effort is ongoing to reduce product cycle time to the market, achieved through design innovations and process optimization.

Part and Mold Design

Fabrication of micro-metal parts by μMIM has been developed and gaining acceptance. It is a net-shape process of fabricating 3D microcomponents by replicating the features of the mold cavity to produce the green part. It is then imperative that the contributions of part and mold design were decisive among the critical factors that influenced finished part quality.

It started by part drafting after material selection, part dimensions, rib design, and stress analysis are among the consideration as illustrated in Fig. 7. Therefore, the design of both the part and mold are interoven as both influenced part quality. However, researchers focused their attention on part design in an effort to combat part shrinkage and other defects which affect the finished part quality at microscale and applied optimization techniques to the process parameters during molding section.

Machine and Process Conditions

Researchers and stakeholders are working very hard to develop further the entire process of μMIM. This involves the development of custom-made micro-injection molding machine(s) and process optimization for best part quality. Attia and Alcock [124] develop a robust DOE to optimize process conditions for multiple quality criteria in micro-injection molding. However, more work still needs to be carried out in terms of molded part quality and process parameters for a clear and thorough understanding of the μMIM process. System development and quality improvement of product is sustained by robust design.

The post-molding processess of μMIM are not left out as debinding, sintering, as well as inspection and quality control have received tremendous attention by researchers. However, the challenge of testing and inspection still remain an issue. This is because most measuring systems are found not suitable for micro-molded parts. Meanwhile, efforts are ongoing to develop suitable inline quality control system [28, 155].

Future Works

An empirical relationship between process parameters and quality response such as: dimensional accuracy, part weight, and mechanical properties will improve finished part quality. Therefore, the following is recommended for further investigation:

1. Instrumentation and control capability of the custom-made μMIM machine needs to be strengthened. This is the act of measuring and monitoring of the processing parameters which influences part quality from the machine.
2. Development and characterization of μMIM feedstock to be guided by a standard or unify principle.
3. Process integration and development to enhance capability and wider application. This could be integration of mixing mechanism and injection process via rapid prototyping and or additive manufacturing techniques with μMIM.
4. A multiple quality characteristics relationship based on process conditions will enhance finished part quality.
5. Shrinkage and warpage measures to cover part dimension less than 10 μm. This will enhance process development of micro-nano and bimodal injection molding.

Conclusions

This study presents a glance evolutionary overview of μMIM. This manufacturing technique is found suitable for large volume production of various consumer products and applications. The following conclusions were drawn:

1. Powder characteristics and sintering temperature greatly influenced part quality; this is monitored by response factors such as dimensional accuracy, mechanical properties, surface quality, shrinkage, and warpage of the finished part.
2. The critical factors that influenced part quality are part design, mold design and fabrication, material selection, process conditions, and machine selection.
3. Part quality is improved with the application of optimization techniques to process parameters which are mold temperature, melt temperature, injection speed, injection pressure, cooling time, packing, and holding parameters.
4. Development of new feedstock and introduction of micro-nano particles improve finished part quality for specific application.
5. Process development continues to reduce cycle time to meet up with market demand, especially for medical and electronics applications.

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