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Design and analysis of feedstock mixing mechanism for micro metal injection moulding

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Abstract

The need for homogeneous metal powder and binder mixing is paramount in injection moulding process as it affect product quality significantly. However available commercial feedstocks may not be suitable especially for production of micro parts with high aspect ratio. Therefore, this research proposes a new mixer design that incorporate mixing and granulation of the feedstock for components production at micro level. Also metal powder/ binder flow in the mixing chamber is investigated. The design specifications and simulation were based on powder loading, powder size and shape, binder formulation, sequence of material addition, mixing time, temperature and shear rate with finite element analysis. The simulation results show a favourable and visible design anticipation of the mixing mechanism and mixed feedstock. Conclusively development of this design will enhance micro metal moulding productivity and improve production cycle time.

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*Keywords:*feedstock; design; mixing mechanism; micro parts; micro metal; injection moulding; flow analysis

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1. Introduction

Industrial production of product begin from selection and preparation of raw material to be used for the manufacture of the finished product. This usually includes adoption of manufacturing techniques and procedure which are exclusively unique for different product development.

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Nomenclature

ρ	density	$\dot{\gamma}$	effective shear rate
$\bar{D}$	rate of deformation tensor	β	a constant parameter with units of time
η_∞	infinite shear viscosity	λ	mixing index
δ	screw tip-barrel wall clearance	$\vec{\tau}$	shear tensor
η	shear viscosity	α	temperature coefficient of viscosity
η_0	zero shear viscosity	a	width of transition region
C(T)	heat capacity	D	barrel diameter
D_A	screw external diameter	D_k	screw core diameter
H	a step function	L	centreline distance
n	dimensionless constant	P	pressure
q	heat flux	r	volumetric heat source
s	screw-screw clearance (s)	t	time
T	temperature	T_0	barrel surface temperature
T_s	screw pitch	V	velocity
z	number of threads		

Therefore, mixing of the constituent element or components in production processing of Pharmaceutical, Chemical, Cement, Food, and Powder Injection Moulding (PIM) products have to achieve efficient and homogenous mixing.

However, homogeneous blending of the constituent elements has been the problem. Investigation of particle mixing mechanisms has received fundamental attention since 1954 as cited in Lancy's study [1]. In general, mixing mechanism of particles are classified into three categories. These are convection, diffusion and shearing mechanisms of mixing. Meanwhile mixers combine these mechanisms to achieve optimum processing condition [1, 2]. But their performance has been hindered by the design and process conditions [3, 4]. Hence, there is a need for optimizing design parameters as well as process conditions. This is for the fact that preparation of homogenous feedstock greatly influences the product quality of micro metal injection moulding.

In recent time numerical simulation and experimental research are ongoing on the suitability of the screw extruders for mixing mechanism [5-12]. Fig. 1 presents a broad classification of mixers based on extrusion principle.

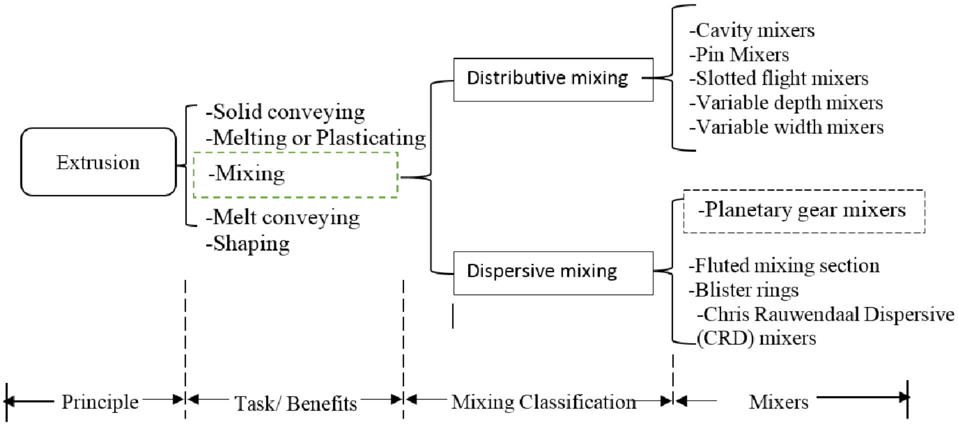

Fig. 1. Mixing mechanism and mixer classification based on plasticising extrusion.

During mixing, a typical fluid flow analysis is characterised either by a Newtonian or non-Newtonian fluid. In this study, the fluid within the mixing chamber was considered as non-Newtonian.This type of fluid exhibits viscoelastic effects.

According to Huang and Kuo [1], computer simulation is a numerical tool that is more cost-effective than carrying out experiments in complex systems. This establishes a basis for design optimization, scale-up, and control of the system. Nevertheless, there are two common numerical approaches for studying particle mixing: the discrete approach and the continuum approach. Meanwhile, the Monte Carlo Method, Cellular Automata, and Discrete Element Method (DEM) were developed based on discrete approach. In addition, researchers now prefer to analyse granular flow with Computational Fluid Dynamics (CFD), for the fact that continuum approach does not account for system size relative to DEM. Flow pattern of mixing particles can be described by dispersive or distributive mixing [14-15], as illustrated in Fig. 2.

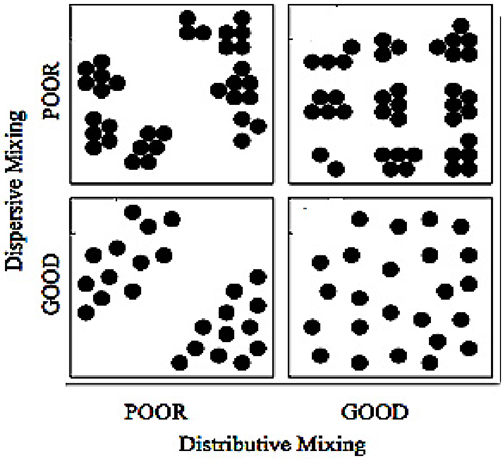

Fig. 2.Dispersive mixing and distributive mixing.

Therefore, the objective of this research is to design a miniature mixer suitable for mixing and granulating the micro metal injection moulding feedstock constituents, based on extrusion principle. The present research will optimize process conditions of the proposed design using simulation to predict the mixing capabilities of the mixer.

2. Materials and methods

2.1. Schematic of the mixer design

The design analysis and consideration were given to powder size and shape, binder formulation and constituents, sequence of material addition, mixing time and temperature, shear rate and rotor speed.

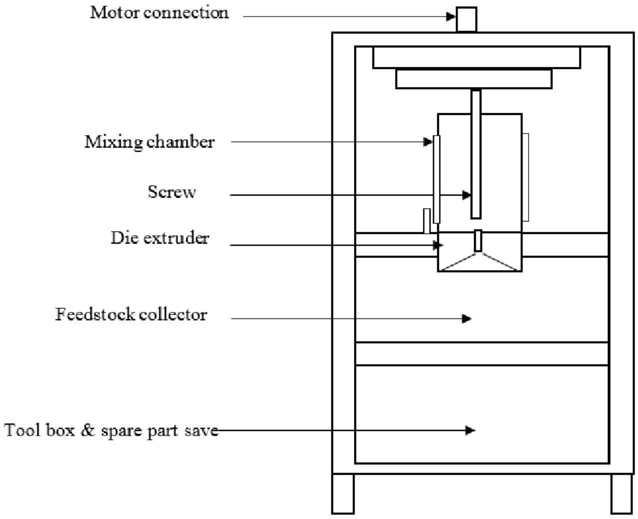

Fig. 3.Schematic of the mixer.

The proposed design shown in Fig. 3 consists of a mixing chamber with screw mixer, a die extruder, and a feedstock collector. The bottom chamber is for keeping tools and spare parts. The design specification for the screw is presented in Table 1.

Table 1: Specification of the double-flighted screw and barrel geometries.

Characteristic variables	Value (mm)
Centreline distance (L)	50
Barrel diameter (D)	61
Screw core diameter (D_k)	38
Screw external diameter (D_A)	60
Screw tip-barrel wall clearance (δ)	0.5
Screw-screw clearance (s)	1
Pitch (T_s)	120
Number of threads (Z)	2

The distance (L) between the screws centre is expressed as:

$$L = \tfrac{1}{2}\left(D_A + D_k\right) + s \tag{1}$$

However, to have proper intermesh between the screws equation (2) must be satisfy [16].

$$\tfrac{L}{(D_A+s)} \geq \cos\left(\tfrac{90}{Z}\right) \tag{2}$$

The energy balance of the system involves input from the electric motor and heating elements. However, the heat transfer analysis of the thermal energy supply by the electric heaters to the mixing chamber undergoes two forms of the transfer system. At inception the heat transfer is dominated by conduction from the heaters to the barrel and between the barrel to the feedstock in solid state, likewise from feedstock to the screw. Meanwhile, as the feedstock transforms from a solid phase to fluid, a convective transfer sets in at this stage within the mixing chamber. But conduction still remains between the fluid interfaces and the barrel as well as between the screws.

2.2. Mathematical Modelling

The analysis of fluid flow were based finite element method, starting with formulation of the substantive derivative, which account for the motion, displacement and non-isothermal energy conservation of the fluid particle within the mixing chamber. The governing equations of fluid flow are as follows:

$$\nabla.\vec{V}=0 \tag{3}$$

$$H(v-\vec{V})+(1-H)\left[\nabla.\vec{\tau}-\nabla p+\rho\left(\frac{\partial v}{\partial t}+v.\nabla\vec{V}\right)\right]=0 \tag{4}$$

$$\rho C(T)\left(\frac{\partial T}{\partial t}+v.\nabla T\right)=T.\nabla v+r-\nabla.q \tag{5}$$

Equation (3) is the continuity equation, equation (4) is the momentum and equation (5) is energy equation. The stress tensor and the shear rate is define by equation (6) and equation (7) respectively, in term of the strain rate tensor.

$$\vec{\tau}=2\eta(\dot{\gamma},T)\vec{D} \tag{6}$$

$$\dot{\gamma}=\sqrt{2\vec{D}:\vec{D}} \tag{7}$$

In this study, Carreau-Yasuda model is adopted for rheology of the fluid particle and shear viscosity is expressed as:

$$\eta=\eta_\infty+(\eta_0-\eta_\infty)[1+(\beta\dot{\gamma})^a]^{\frac{(n-1)}{a}} \tag{8}$$

Since the flow is non-isothermal, then temperature has to be accounted for; by a factor known as the Arrhenius law $H(T)$. The shear viscosity is

$$\eta=\eta_0(\gamma)H(T) \tag{9}$$

The approximate Arrhenius law is expressed as:

$$H(T)=\exp[-\alpha(T-T_0)] \tag{10}$$

2.3. Simulation

Fluid simulation within the mixing chamber wase carried out based on Finite Element Method (FEM), using ANSYS 14.0. This involves five steps namely i) Geometry, ii) Mesh, iii) Setup, iv) Solution, and v) Results.

The flow domain of the system is illustrated in Fig. 4, showing the screws and barrel mesh superposition at initial location with 1080 elements and 2302 nodes.

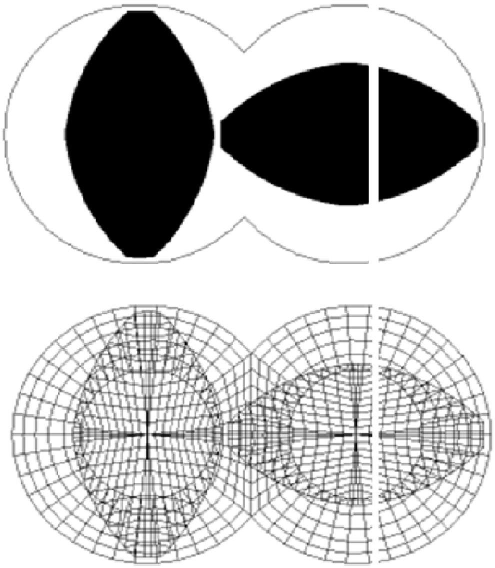

Fig. 4. Flow domain geometry and meshes at the initial position.

This study proposes to mix Aluminum Powder, High Density Polyethylene (HDPE), Paraffin Wax (PW) and Stearic Acid (SA) for the preparation of micro metal injection moulding feedstock. However, to investigate the behaviour of the feedstock; some basic assumptions were made such as the fluid is non-Newtonian and exhibits laminar flow with high viscosity; the flow is non-isothermal, incompressible, and nonslip condition existed at barrel wall and screw flight and the influence of both inertia and gravity effects were neglected. The proprieties of the binder are represented in Table 2.

Table 2: Binder properties [17].

Properties	Binder Components		
	HDPE	PW	SA
Specific heat capacity/J·K−1·kg−1	2200	2700	1700
Thermal conductivity/W·m−1·K−1	0.30	0.14	0.35
Temperature(T_{ox}) K	463	373	383
Zero-shear-rate viscosity (η_∞) Pa.s	300	0.009	0.007
Activation energy (E_x) /j.mol-1	26300	4400	0

The simulation focused to estimate the mixing index (λ) from the local shear rate ($\dot{\gamma}$) and the local intensity of the vorticity (ω') expressed as [18]:

$$\lambda = \frac{\dot{\gamma}}{\dot{\gamma} + \omega'} \tag{11}$$

3. Results and discussion

3.1. Results

The simulation was implemented to accommodate 20 steps within the duration of the each run. This allows monitoring at every 9°covered by the rotor rotation from the reference axis. Three trials were carried out and results are presented in Fig. 5 to 8.

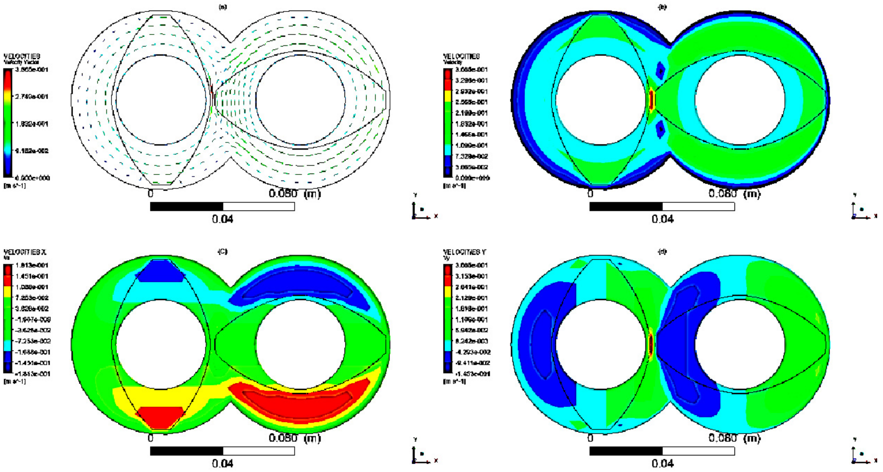

Fig. 5. (a) Velocity vector; (b) flow velocity; (c) Velocity along x- direction; (d) Velocity along y-direction at 30 rpm.

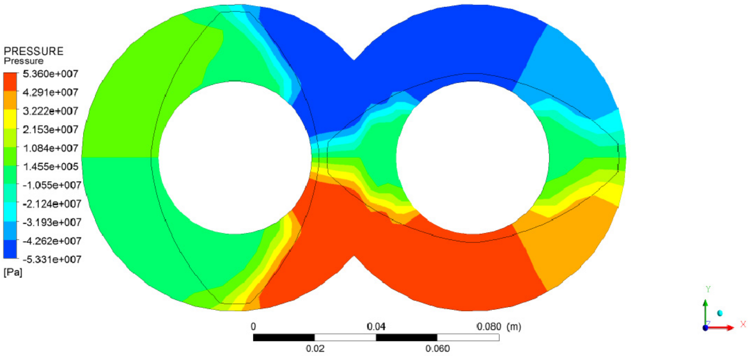

Fig. 6. Contour plot of pressure of flow domain at 30 rpm.

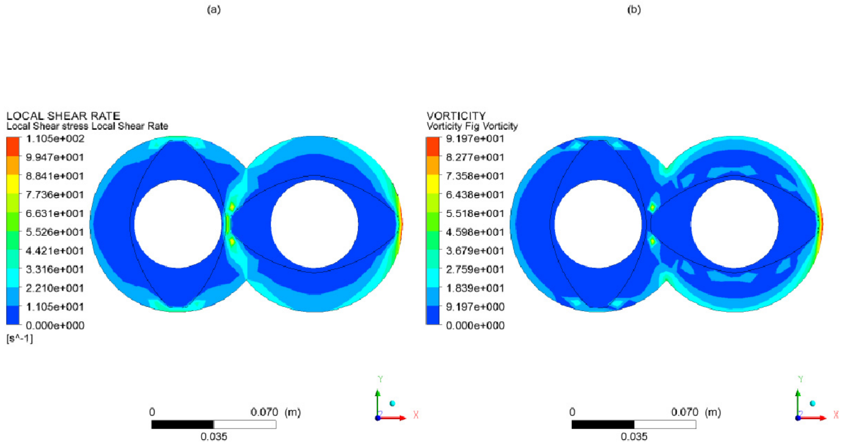

Fig. 7.(a) Local shear rate; (b) local intensity of the vorticity at 30 rpm.

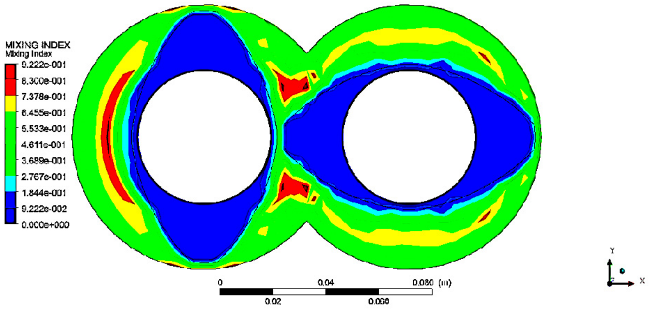

Fig. 8.Mixing index at 30 rpm.

3.2. Discussion

Fig. 5a, shows the velocity vector of the co-rotating twin-screw and fluid flow within the mixing chamber with a maximum velocity of 0.3665 ms-1 in a counter clockwise direction as illustrated by the vectors profile. This is a prediction of velocity distribution across the twin-screw profile within the flow domain. Fig. 5b is a colour map of the velocity showing the magnitudes according to different colours and the maximum velocity was found to be 0.35368 ms-1. In addition, Fig. 5c depicts velocity along the *x*-direction (V_x) with a minimum of -0.1813 ms-1 and maximum of 0.1813 ms-1. While, Fig. 5d depicts velocity along the *y*-direction (V_y) having a minimum value of -0.14523 ms-1 and maximum of 0.36647 ms-1. The result of pressure prediction shown in Fig. 6 recorded high impact pressure at the lower part of the barrel towards the centre with a maximum of 53.6 MPa. Local shear rate and vorticity of the flow domain show similar trend but the local shear rate was observed to be more pronounced at the centre having a maximum value of 110. 52 s-1, as shown in Fig. 7a.

The trend of the simulation results suggests the expected swapping of the screws between the two lobes in a co-rotating twin-screw mixer, which provide the required homogenous of the feedstock mix. However, the simulation trials at speed of 25 rpm and 35 rpm show an increased in velocity and pressure but less impact on the mixing index. Fig. 8 illustrates the mixing index at 30 rpm with a maximum value of 0.922. These simulation results are in good agreement with findings by other researchers [7, 11].

4. Conclusions

The physics of the flow domain were modeled using FEM based on the mixed Galerkin method and implemented with ANSYS 14.0, Fluid Flow (POLYFLOW) software. This allows a wide scope of random trial but controlled by optimisation techniques to account for efficient product design. Based on the simulation results, following conclusions can be drawn.

- The miniature mixer proposed in this paper will be a convenient bench top and suitable for micro metal injection moulding feedstock preparation. Dispersive mixing by planetary gear mixers show an efficient mixing of feedstock components.
- High mixing index value of 0.922 indicates better homogeneous mix of the feedstock which will result in quality injection molded product.
- With the increase of screw speed, the velocities along x and y direction increase which indicate better mixing feedstock materials.
- The mixer will be suitable for a wide range of materials which are hard, medium hard brittle and fibrous sample.
- Development of this mixer will enhance micro metal moulding productivity and improve production cycle time.

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