Thermal Characterisation of Binder Constituents and Wax-Based Aluminium Metal Injection Moulding Feedstock for Micro-Metal Parts

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Abstract

Thermal decomposition behaviours of the binder constituents have been identified to influenced the quality of metal injection moulding (MIM) feedstock and sintered parts. This research investigates the thermal characterisation of the binder constituents and wax-based aluminium MIM feedstock. The binder system is composed of paraffin wax (PW) – 65 wt.%, high density polyethene (HDPE) – 30 wt.% and Stearic acid (SA) – 5 wt.%. While, the wax-based aluminium MIM feedstock is formulated with the proportions of the binder constituents and 99.999% pure aluminium powder at solid loading of 62 vol.%. Thermal characterisation technique employed for the evaluation of the binder constituents and wax-based aluminium MIM feedstock were differential scanning calorimetry and thermogravimetric analysis (TGA). Significant changes were observed for the binder constituents at various temperatures 45 ˚C and 60 ˚C (PW), 135 ˚C (HDPE), 75 ˚C (SA) and 45 ˚C, 60 ˚C, 135 ˚C (Wax-based aluminium MIM feedstock) on the DSC profiles. While TGA results revealed that binder constituents can be removed completely around 580 ˚C from the wax-based aluminium MIM feedstock. Thermal behaviour of the binder system established will be useful for setting suitable injection moulding temperature, development of the thermal profile(s) for debinding and sintering processes of the aluminium MIM micropart production.

Keywords: aluminium, metal injection moulding, paraffin wax, thermal characterisation, wax-based feedstock.

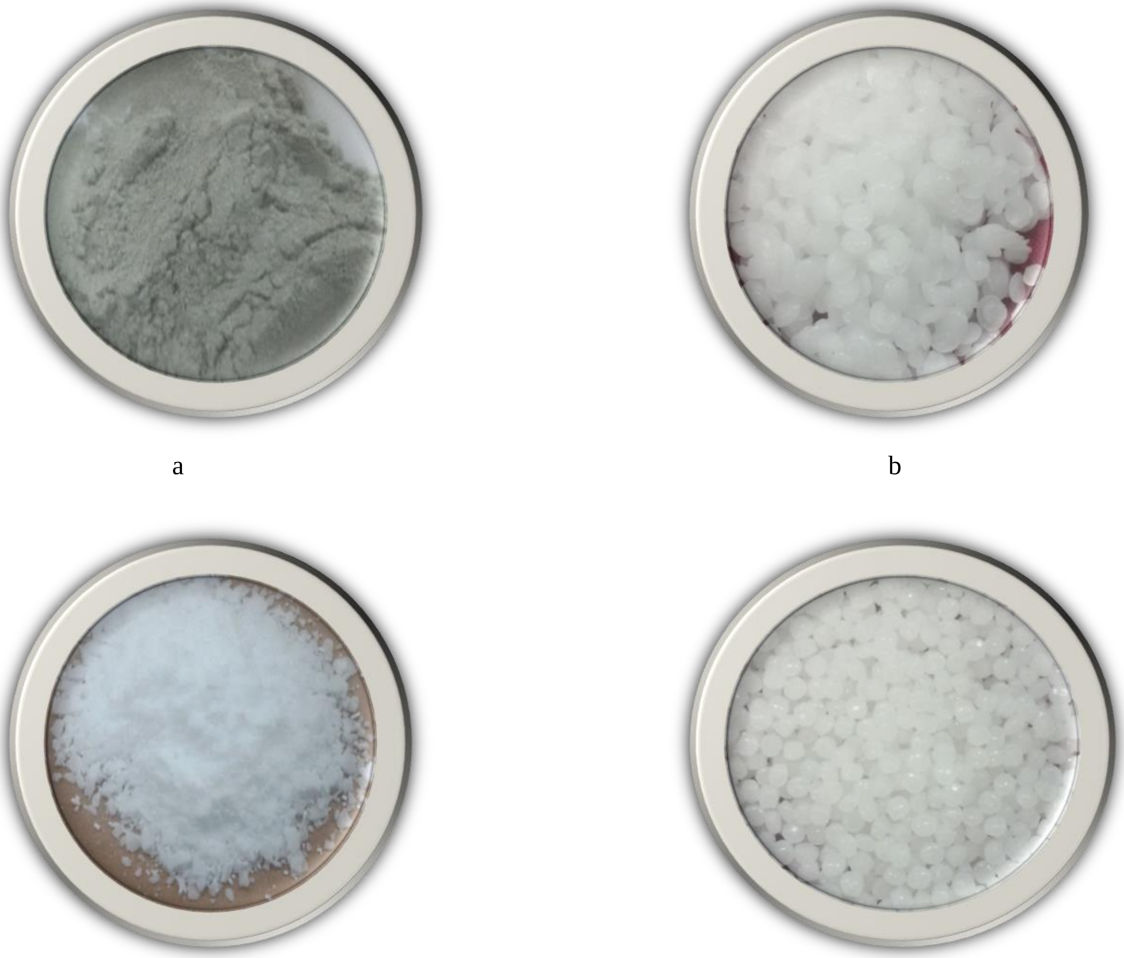
1. Introduction

Metal injection moulding (MIM) is an advanced powder metallurgy technique which integrate plastic injection moulding with powder injection moulding, originally developed for processing ceramic parts. This microfabrication technique has been utilized for various metal powder processing ranging from ferrous and non-ferrous metals [1–3]. However, aluminium MIM is still reported as empirical findings and industrial aluminium MIM feedstock is yet to be established as obtained for ferrous metals. This may be attributed to quite a number of issues which include: formation of thin oxide layer, low melting point, highly reactivity, difficulty in achieving full densification during sintering [4]. Despite these challenges encountered, processing of aluminium and aluminium alloys [4–8] by MIM technique is explored.

Formulation and mixing of powder-binder constituents is the first process of the technique, then follow by injection moulding, debinding and sintering processes. Therefore, success of the MIM for production of defect-free and high-quality sintered part; strongly depends on binder system. Binder systems developed for various metal powder injection moulding can be categorised as follow: petroleum, green and/or water soluble [9–15]. The petroleum-based are further grouped into wax-based [7] and polymer-based [12] binder systems. Though a binder system usually contains two or more components that are carefully chosen for specific task. For instance, the polymer provides stability and strength required, stearic acid usually used as dispersant and wax is added to enhance flowability. The wax-based binder systems were found to be suitable for powder injection moulding technique [2]. Meanwhile, thermal behaviour of a binder system is investigated in order to determine suitable injection moulding temperature. In addition, it is used for development of suitable thermal profiles for debinding and sintering processes of the MIM feedstock. Therefore, this study examines thermal characterisation of binder constituents and wax-based aluminium MIM feedstock.

2. Materials and methods

The composition of the binder system and proportions of the constituents is as follows: paraffin wax (PW) – 65 wt.%, high density polyethene (HDPE) – 30 wt.% and stearic acid (SA) – 5 wt.%. Aluminium powder with 99.999% purity was used for the formulation of the feedstock. The wax-based aluminium MIM feedstock is formulated with the proportions of the binder constituents at solid loading of 62 vol.%. [2, 7]. Samples of the aluminium powder and binder constituents as received from the supplier are shown in Fig. 1, prepared samples of aluminium MIM feedstock are shown in Fig. 2. Physical properties of the binder constituents and aluminium powder are shown in Table 1. Density of the aluminium MIM feedstock is theoretically evaluated to be 2.0284 g/cm^3 at 62 vol.% solid loading.



a b c d

Fig. 11. Samples of the powder used and binder constituents as received: a – Al; b – PW; c – SA; d – HDPE

a b c

Fig. 2. Samples of the wax-based aluminium MIM feedstock as prepared: a – 3 mm pelletise; b – granulated; c – 8 mm extruded

Table 1. Physical properties of wax-based binder constituents and aluminium powder

S/N	Binder constituents/ powder	Density, g/cm^3	Chemical structural/ symbol
1	PW	0.92	C_nH_{2n+2}
2	HDPE	0.96	$(C_2H_4)_n$
3	SA	0.94	$CH_3(CH_2)_{16}COOH$ or $C_{18}H_{36}O_2$
4	Aluminium	2.70	Al

Thermal characterisation of the binder constituents and wax-based aluminium MIM feedstock samples was investigated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) [11, 15]. The DSC is used for the determination of the melting point of the binder constituents and aluminium MIM feedstock samples. About 15 mg of the samples were carefully weighed and sealed in aluminium crucibles of 40 µl, placed in the DSC chamber and set at 10 ˚C/min of heating rate, and readings were recorded from 30 ˚C to 210 ˚C for various samples of the binder constituents and aluminium MIM feedstock.

Furthermore, the thermal stability and decomposition rate of the binder constituents and aluminium MIM feedstock samples were investigated using TGA. About 20 mg of the samples each was carefully weighed and loaded into the TGA machine and the analysis was conducted under vacuum atmospheric conditions. The tests were conducted from 25 ˚C to 600 ˚C at a scanning rate of 10 ˚C/min.

3. Results and discussion

Results of the thermal characterisation of the binder constituents and aluminium MIM feedstock samples investigated are shown in Figs. 3 and 4. The DSC spectrum of the wax-based aluminium MIM feedstock shown in Fig. 3 reveal the homogeneity of the of powder-binder mixture as various peaks depict the presence of binder constituents (PW, HDPE and SA).

Similarly, the TGA of the binder constituents and aluminium MIM feedstock samples were investigated, results obtained are shown in Figure 4. It was observed that no residue of PW and SA were obtained at 575 ˚C. This indicates the suitability of multi-step debinding; involving solvent extraction to be followed by thermal debinding. In addition, it is evident from the TGA spectra that the wax-based aluminium MIM feedstock gain more weight from 525 ˚C; this phenomenon characterising unalloyed aluminium was reported by Schaffer and Hall [16]. Furthermore, some notable thermal characteristics of the binder constituents and aluminium MIM feedstock is hereby summarised in Table 2, based on DSC and TGA respectively.

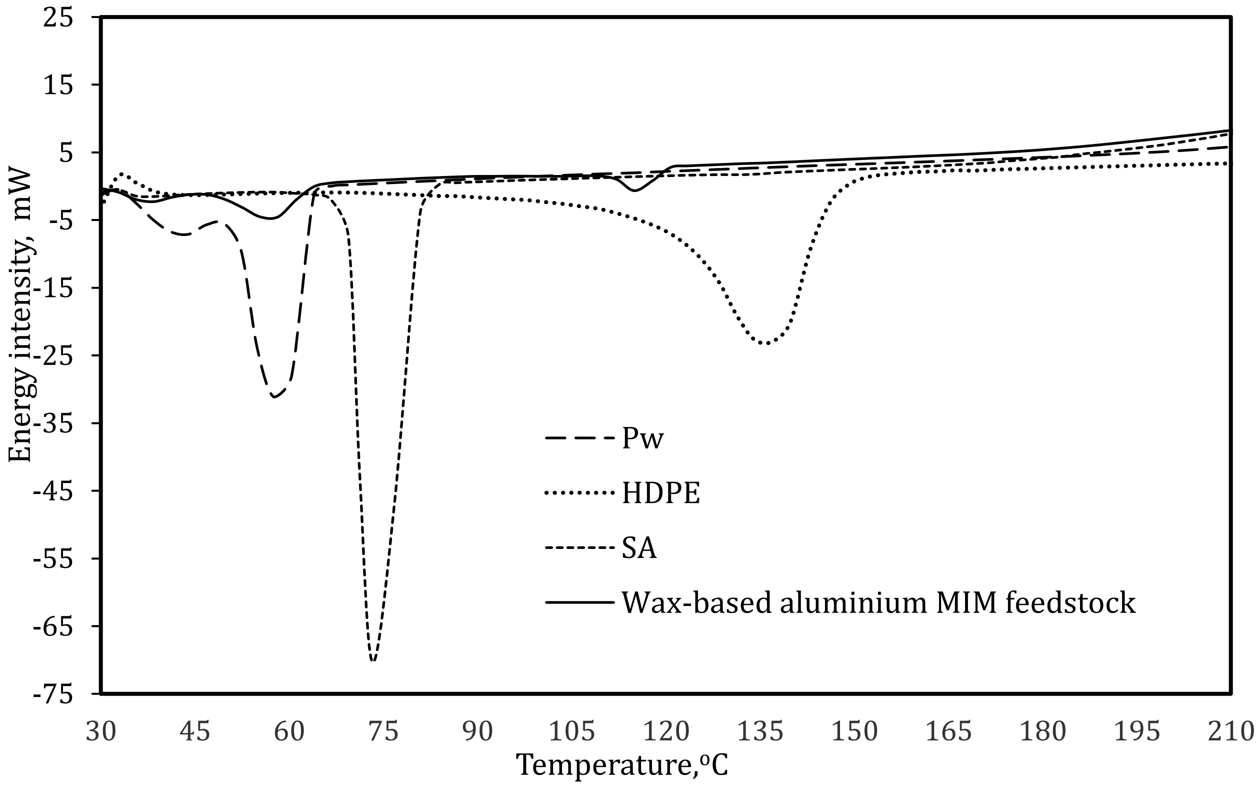


Fig. 3 DSC thermogram of the binder constituents and wax-based aluminium MIM feedstock

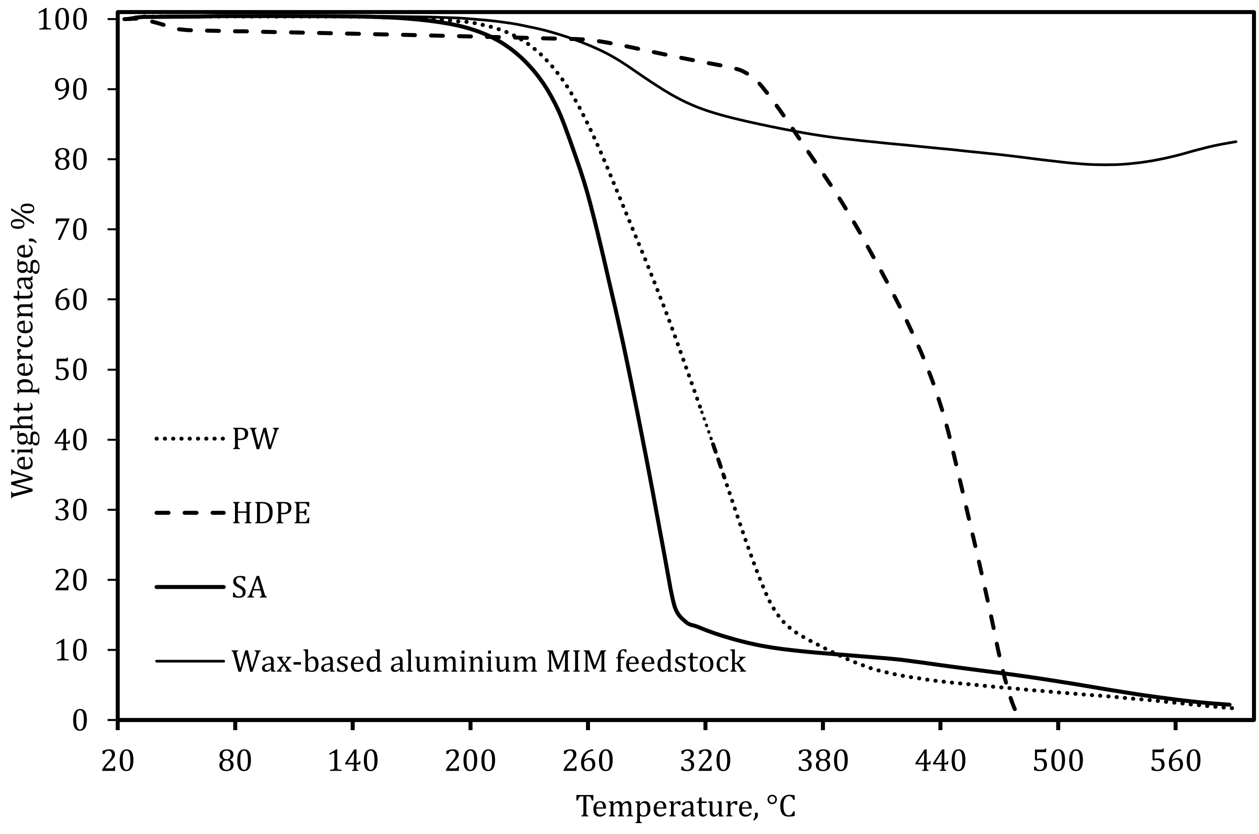


Fig. 4. TGA of the binder constituents and wax-based aluminium MIM feedstock

Table 2. Thermal characteristics of the binder constituents and wax-based aluminium MIM feedstock

S/N	Binder constituents/ feedstock	Melting Point, °C	Weight loss start temperature, °C	Rapid weight loss temperature, °C	Weight loss end temperature, °C
1	PW	58	182	242	481
2	HDPE	139	181	346	477
3	SA	72	180	233	580
4	Aluminium MIM feedstock	660	188	277	525

Comparative analysis of the results shown in Table 2, weight loss of the binder constituents began from 180 ˚C. Therefore, injection moulding temperature can conveniently be set slightly below this temperature within the range 150–179 ˚C. Furthermore, development of the combine or separate thermal profile(s) for debinding and sintering must consider at least a soaking/ holding time at 346–480˚C to burn-off the polymer constituents in order to produce carbon free parts.

4. Conclusions

The following conclusions are drawn:
1. Melting and degradation temperature range of the binder constituents were established.
2. Significant changes were observed for the wax-based aluminium MIM feedstock at various degradation temperatures of the binder constituents, indicating homogenous mixture of powder-binder.
3. The degradation temperature determined for the binder constituents and wax-based aluminium MIM feedstock will be useful in setting injection moulding temperature, development of the thermal profiles for debinding and sintering processes using this binder system.

References

1. GERMAN, R. M. Powder injection molding. New Jersey, USA, Metal powder industries federation, 1990. ISBN-13 978-0918404954.
2. GERMAN, R. M. Powder injection molding-Design and applications. Innovative materials solutions, USA, 2003. ISBN 0-9727642-0-8.
3. GERMAN, R. M. Progress in titanium metal powder injection molding. *Materials,* vol. 6 (2013), no. 8, pp. 3641-3662.
4. LIU, Z. Y., SERCOMBE, T. B., SCHAFFER, G. B. Metal injection moulding of aluminium alloy 6061 with tin. *Powder Metallurgy*, vol. 51 (2008), no. 1, pp. 78-83.
5. PINWILL, I. E., EDIRISINGHE, M. J., BEVIS, M. J. Fabrication of aluminium components by injection moulding: Role of carbon residue caused by removal of the organic vehicle. *Journal of Materials Science Letters*, vol. 10 (1991) no. 18, pp. 1107-1110.
6. JOYS, J., KASLER, R., RAMSEY, C. Aluminum MIM: New advanced powders and feedstock achieve higher densities. *Powder Injection Moulding International,* vol. 8 (2014), no. 2, pp. 75-79.
7. ABDOOS, H., KHORSAND, H., YOUSEFI, A. A. Torque rheometry and rheological analysis of powder-polymer mixture for aluminum powder injection molding. *Iranian Polymer Journal*, vol. 23 (2014), no. 10, pp. 745-755.
8. KATOU, K., MATSUMOTO, A. Application of Metal Injection Molding to Al Powder. *Journal of the Japan Society of Powder and Powder Metallurgy,* vol. 63 (2016), no. 7, pp. 468-472.
9. WEN, G., CAO, P., GABBITAS, B., ZHANG, D., EDMONDS, N. Development and design of binder systems for titanium metal injection molding: An overview. *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science A,* vol. 44 (2013), no. 3, pp. 1530-1547.
10. LADO-Touriño, I. MERODIO-PEREA, R. G. Molecular Dynamics Simulations of Sustainable Green Binders for Metal Injection Molding. *Sustainability*, vol. 17 (2025), no. 5, pp. 2263-2279.
11. MOMENI, V., SHAHROODI, Z., GONZALEZ-GUTIERREZ, J., HENTSCHEL, L., DURETEK, I. SCHUSCHNIGG,

S., KUKLA, C., HOLZER, C. Effects of Different Polypropylene (PP)-Backbones in Aluminium Feedstock for Fused Filament Fabrication (FFF). *Polymers*, vol. 15 (2023), no. 14, pp. 3007-3025.

12. HANEMANN, T., WEBER, O. Polymethylmethacrylate/polyethyleneglycol-based partially water soluble binder system for micro ceramic injection moulding. *Microsystem Technologies-Micro-and Nanosystems-Information Storage and Processing Systems,* vol. 20 (2014), no, 1, pp. 51-58.
13. AGGARWAL, G., PARK, S. J., SMID, I., GERMAN, R. M. Master decomposition curve for binders used in powder injection molding. *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science*, vol. 38 (2007), no. 3, pp. 606-614.
14. ZOU, H., CHEN, M., FU, Y., XIONG, H., ZHANG, l., ZHOU, K. Microstructure and mechanical properties of complex-shaped 7075 aluminium alloy prepared using modified polyoxymethylene-based feedstock. *Trans. Nonferrous Met. Soc. China*, vol. 34 (2024), no. 11, pp. 3862−3875.
15. LIM, K., HAYAT, M. D., JENA, K. D., ZHANG, W., Li, L. CAO, P. Interactions of polymeric components in a POM-based binder system for titanium metal injection moulding feedstocks. *Powder Metallurgy*, vol. 66 (2023), no. 4, pp. 355-364.
16. SCHAFFER, G. B., HALL, B. J. The influence of the atmosphere on the sintering of aluminum. *Metallurgical and Materials Transactions A*, vol. 33 (2002), no. 10, pp. 3279-3284.