

**APPLICATION OF RESTAURANT WASTE LIPIDS (RWL) AS A BINDER
COMPONENT IN METAL INJECTION MOULDING**

AZRISZUL BIN MOHD AMIN

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For my beloved mother PUAN HJH ZAMALIAH BTE SURATDI,
my loving wife SITI NURFAIZAH BINTI MOHSAN, my sons MUHAMMAD
AQEEL IFWAT, AHMAD AL-SHAREEF, my daughters KHAYRA ZAFIRAH,
AREEFA NAFEESAHI, my only sister and her husband INTAN KARTINI BTE
MOHD AMIN, DR. HASMADI BIN HASSAN

“THANK YOU for your endless support”



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In the name of ALLAH S.W.T, The Most Gracious and The Most Merciful,

Greeting and Blessing to Prophet Muhammad S.A.W

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ABSTRACT

Application of Restaurant Waste Lipids (RWL) is introduced as binder component in metal injection moulding since it's contains rich amounts of free fatty acids which is suitable as secondary binder components. Different binder formulation of RWL and Polypropylene (PP) were prepared as the binders and the mixture of these binders with water atomized 316L powder were obtained. The suitability application of RWL as binder component was monitored base on mixing condition, rheological characteristic, injection moulding, debinding and sintering process. Mixing time of 90 minutes was obtained as suitable mixing time for producing good homogenise feedstock base on mixing the polypropylene (PP) and RWL. Binder ratio of 50/50 weight percentage between PP and RWL was obtained to be good binder ratio although all binder ratio of 60/40, 40/60 and 30/70 shows pseudoplastic behavior. Taguchi method was successfully employed for optimizing the injection moulding parameters which consists of injection temperature, mould temperature, pressure, packing time, injection time, speed and cooling time. It was found that factors that contribute in injecting good part density and strength were temperature, pressure and speed. Extraction process of RWL using solvent debinding process indicates that hexane solution with temperature of 60°C and solvent to feeds ratio of 7:1 were better as compare to heptane with respect to fastest time removal. Good thermal debinding process under air atmosphere condition with temperature of 400°C and heating rate of 30°C/min was obtained. Sintering of the thermal debound parts also shows good mechanical properties and microstructure of 316L stainless steel parts.

ABSTRAK

Penggunaan sisa buangan lemak dan minyak dari restoran makanan telah digunakan sebagai komponen bahan pengikat dalam pembuatan pembentukan suntikan logam. Nisbah percampuran yang berbeza antara RWL dan polimer polypropylene (PP) dihasilkan dan nisbah percampuran bahan pengikat yang berbeza ini dicampurkan bersama serbuk logam keluli tahan karat 316L. Kebolehan bahan ini sebagai komponen bahan pengikat dalam menghasilkan bahan suapan serbuk logam 316L ditunjukkan dari segi percampuran sekata, sifat reologi, pembentukan suntikan, proses pembuangan bahan pengikat dan pensinteran. Masa adunan 90 minit menjadi pilihan berdasarkan campuran yang sekata antara bahan pengikat. Nisbah 50/50 berat bahan pengikat antara polimer dan minyak buangan dari restoran dipilih berdasarkan analisa yang dilakukan walaupun semua nisbah yang terdiri dari 60/40, 40/60 dan 30/70 didapati boleh digunakan sebagai nisbah bahan pengikat. Dalam mencari parameter acuan suntikan yang optimum bagi isipadu dan kekuatan komponen yang dihasilkan, kaedah rekabentuk eksperimen Taguhi digunakan dan mendapat bahawa faktor suhu suntikan, suhu acuan dan tekanan memainkan peranan utama bagi penghasilan komponen suntikan yang mempunyai ketumpatan dan kekuatan yang baik. Pengekstrakkan bahan buangan lemak dan minyak dari komponen menggunakan pelarut hexane didapati lebih berkesan dari bahan pelarut heptane dengan suhu 60°C dengan nisbah berat pelarut dan komponen sebanyak 7:1 adalah lebih baik berdasarkan faktor singkatan masa. Pembuangan bahan pengikat polimer menggunakan kaedah haba dalam udara terbuka dengan suhu 400°C dengan kadar 30°C/min peningkatan suhu adalah lebih baik tanpa sebarang kecacatan pada komponen berlaku. Proses pensinteran terhadap bahan yang telah melalui proses pembuangan polimer menghasilkan pembentukan komponen yang baik dari segi sifat mekanikal dan mikrostruktur bahan 316L keluli tahan karat.

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REFERENCES

1. G. H. Brandtland, “United Nation Report of the World Commission on Environment and Development (Our Common Future),” 1987.
2. S. N. Gan, “Environmental pollution by polymers,” 2007.
3. B. M. Popkin, N. Carolina, and C. Hill, “Urbanization, Lifestyle Changes and the Nutrition,” *World Dev.*, vol. 27, no. 11, pp. 1905–1916, 1999.
4. A. O. Alade, A. T. Jameel, S. A. Muyubi, M. I. A. Karim, and M. Z. Alam, “Removal of Oil and Grease As Emerging Pollutants of Concern (EPC) in Wastewater Stream,” *IIUM Eng. J.*, vol. 12, no. 4, pp. 161–169, 2011.
5. H. Chan, “Removal and recycling of pollutants from Hong Kong restaurant wastewaters,” *Bioresour. Technol.*, vol. 101, no. 17, pp. 6859–6867, 2010.
6. “Malaysian Palm Oil Council (MPOC) Official Website,” *Malaysian Palm Oil Board (MPOB)*, 2013..
7. M. V. Madurwar, R. V. Ralegaonkar, and S. A. Mandavgane, “Application of agro-waste for sustainable construction materials: A review,” *Constr. Build. Mater.*, vol. 38, pp. 872–878, 2013.
8. J. Hidalgo, A. Jiménez-Morales, and J. M. Torralba, “Thermal stability and degradation kinetics of feedstocks for powder injection moulding - A new way to determine optimal solid loading?,” *Polym. Degrad. Stab.*, vol. 98, no. 6, pp. 1188–1195, 2013.
9. J. M. Adames, “Characterization of Polymeric Binders for Metal Injection Molding (MIM) Process,” 2007.
10. D. Checot-Moinard, C. Rigollet, and P. Lourdin, “Powder injection moulding PIM of feedstock based on hydrosoluble binder and submicronic powder to manufacture parts having micro-details,” *Powder Technol.*, vol. 208, no. 2, pp. 472–479, 2011.

11. M.-S. Huang and H.-C. Hsu, "Effect of backbone polymer on properties of 316L stainless steel MIM compact," *J. Mater. Process. Technol.*, vol. 209, no. 15–16, pp. 5527–5535, Aug. 2009.
12. S. Supriadi, E. R. Baek, C. J. Choi, and B. T. Lee, "Binder system for STS 316 nanopowder feedstocks in micro-metal injection molding," *J. Mater. Process. Technol.*, vol. 187–188, pp. 270–273, 2007.
13. G. Herranz, R. Nagel, B. Levenfeld, R. Zauner, and J. M. Torralba, "Influence of the Powder Surface Treatment with Stearic Acid on Powder Injection Moulding of M2 HSS Using a HDPE Based Binder," *Euro PM2004*, 2004.
14. CustomPartNet, "Metal Processes Injection Molding," *CustomPartNet*, 2017. [Online]. Available: <http://www.custompartnet.com/wu/metal-injection-molding>.
15. L. Shen and D.-K. Zhang, "An experimental study of oil recovery from sewage sludge by low-temperature pyrolysis in a fluidized-bed," *Fuel*, vol. 82, no. 4, pp. 465–472, 2003.
16. M. Canakci, "The potential of restaurant waste lipids as biodiesel feedstocks," *Bioresour. Technol.*, vol. 98, no. 1, pp. 183–190, 2007.
17. P. Setasuwon, A. Bunchavimonchet, and S. Danchaivijit, "The effects of binder components in wax/oil systems for metal injection molding," *J. Mater. Process. Technol.*, vol. 196, no. 1–3, pp. 94–100, 2008.
18. W. J. Tseng and D. Chiang, "Influence of molding variables on defect formation and mechanical strength of injection-molded ceramics," *J. Mater. Process. Technol.*, vol. 84, no. 1–3, pp. 229–235, 1998.
19. S. V Atre, R. K. Enneti, S. J. Park, and R. M. German, "Master decomposition curve analysis of ethylene vinyl acetate pyrolysis : Influence of metal powders," *Powder Metall.*, vol. 51, no. 4, pp. 368–375, 2008.
20. B. Hausnerova, "Rheological characterization of powder injection molding compounds," *Polimery/Polymers*, vol. 55, no. 1, pp. 3–11, 2010.
21. G. S. Upadhyaya, "Powder Injection Moulding," in *POWDER METALLURGY TECHNOLOGY*, Cambridge International Science Publishing, 2002, p. 131.
22. A. Mannschatz, A. Müller, and T. Moritz, "Influence of powder morphology on properties of ceramic injection moulding feedstocks," *J. Eur. Ceram. Soc.*, vol. 31, no. 14, pp. 2551–2558, 2011.

23. K. Sharmin and I. Schoegl, "Two-step debinding and co-extrusion of ceramic-filled PEBA and EVA blends," *Ceram. Int.*, vol. 40, no. 9 PART B, pp. 14871–14879, 2014.
24. F. A. Çetinel, W. Bauer, R. Knitter, and J. Haußelt, "Factors affecting strength and shape retention of zirconia micro bending bars during thermal debinding," *Ceram. Int.*, vol. 37, no. 7, pp. 2809–2820, 2011.
25. F. Mohd Foudzi, N. Muhamad, A. Bakar Sulong, and H. Zakaria, "Yttria stabilized zirconia formed by micro ceramic injection molding: Rheological properties and debinding effects on the sintered part," *Ceram. Int.*, vol. 39, no. 3, pp. 2665–2674, Apr. 2013.
26. S. Md Ani, A. Muchtar, N. Muhamad, and J. A. Ghani, "Binder removal via a two-stage debinding process for ceramic injection molding parts," *Ceram. Int.*, vol. 40, no. 2, pp. 2819–2824, 2014.
27. K. H. Kate, R. K. Enneti, V. P. Onbattuvelli, and S. V. Atre, "Feedstock properties and injection molding simulations of bimodal mixtures of nanoscale and microscale aluminum nitride," *Ceram. Int.*, vol. 39, no. 6, pp. 6887–6897, 2013.
28. L. Gorjan, T. Kosmač, and A. Dakskobler, "Single-step wick-debinding and sintering for powder injection molding," *Ceram. Int.*, vol. 40, no. 1 PART A, pp. 887–891, 2014.
29. M. H. Ismail, A. T. Sidambe, I. A. Figueroa, H. A. Davies, and I. Todd, "Effect of powder loading on rheology and dimensional variability of porous, pseudo-elastic NiTi alloy produced by metal injection moulding (MIM) using a partly water soluble binder system," *Proc. World Powder Metall. Congr. Exhib. World PM 2010*, vol. 4, no. Mim, p. 347, 2010.
30. N. De Freitas Daudt, M. Bram, A. Paula Cysne Barbosa, C. Barbosa, A. M. Laptev, and C. Alves Jr., "Manufacturing of highly porous titanium by metal injection molding in combination with plasma treatment," *J. Mater. Process. Tech.*, vol. 239, pp. 202–209, 2017.
31. R. K. Enneti, S. J. Park, R. M. German, and S. V. Atre, "Review: Thermal Debinding Process in Particulate Materials Processing," *Mater. Manuf. Process.*, vol. 27, no. 2, pp. 103–118, 2012.

32. Y. Tao, Z. Li, and K. Zhou, "Effects of debinding atmosphere on the microstructure and sintering densification of nickel ferrite," *Ceram. Int.*, vol. 39, no. 1, pp. 865–869, 2013.
33. R. German, "Progress in Titanium Metal Powder Injection Molding," *Materials (Basel)*., vol. 6, no. 8, pp. 3641–3662, 2013.
34. H. Ye, X. Y. Liu, and H. Hong, "Fabrication of metal matrix composites by metal injection molding-A review," *J. Mater. Process. Technol.*, vol. 200, no. 1–3, pp. 12–24, 2008.
35. R. M. German, "Metal powder injection molding (MIM): key trends and markets," in *Handbook of Metal Injection Moulding*, Woodhead Publishing, 2012.
36. G. Wen, P. Cao, B. Gabbitas, D. Zhang, and N. Edmonds, "Development and design of binder systems for titanium metal injection molding: An overview," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 44, no. 3, pp. 1530–1547, 2012.
37. X. Kong, T. Barriere, and J. C. C. Gelin, "Determination of critical and optimal powder loadings for 316L fine stainless steel feedstocks for micro-powder injection molding," *J. Mater. Process. Technol.*, vol. 212, no. 11, pp. 2173–2182, Nov. 2012.
38. M. A. Omar, I. Subuki, N. S. Abdullah, N. M. Zainon, and N. Roslani, "Processing of Water-atomised 316L Stainless Steel Powder Using Metal-injection Processes," *J. Eng. Sci.*, vol. 8, pp. 1–13, 2012.
39. M. R. Raza, F. Ahmad, M. A. Omar, and R. M. German, "Effects of cooling rate on mechanical properties and corrosion resistance of vacuum sintered powder injection molded 316L stainless steel," *J. Mater. Process. Technol.*, vol. 212, no. 1, pp. 164–170, 2012.
40. M. I. H. Chua, A. B. Sulong, M. F. Abdullah, and N. Muhamad, "Optimization of injection molding and solvent debinding parameters of stainless steel powder (SS316L) based feedstock for metal injection molding," *Sains Malaysiana*, vol. 42, no. 12, pp. 1743–1750, 2013.

41. N. Tuncer, M. Bram, A. Laptev, T. Beck, A. Moser, and H. P. Buchkremer, "Study of metal injection molding of highly porous titanium by physical modeling and direct experiments," *J. Mater. Process. Technol.*, vol. 214, no. 7, pp. 1352–1360, 2014.
42. G. Herranz, R. Nagel, B. Levenfeld, and R. Zauner, "Powder Injection Moulding: Influence of the Powder Surface Treatment with Stearic Acid on Powder Injection Moulding of M2 HSS Using a HDPE Based Binder," *Eur. Congr. Exhib. Powder Metall. Eur. PM Conf. Proc.*, 2004.
43. Ö. Özgün, H. Ö. Gülsøy, R. Yilmaz, and F. Findik, "Injection molding of nickel based 625 superalloy: Sintering, heat treatment, microstructure and mechanical properties," *J. Alloys Compd.*, vol. 546, pp. 192–207, 2013.
44. E. Klar and P. K. Samal, *Powder Metallurgy Stainless Steel-Processing, Microstructure and Properties*, First prin. ASM International The Materials Information Society, 2007.
45. L. Castro, S. Merino, B. Levenfeld, A. Várez, and J. M. Torralba, "Mechanical properties and pitting corrosion behaviour of 316L stainless steel parts obtained by a modified metal injection moulding process," *J. Mater. Process. Technol.*, vol. 143–144, no. 1, pp. 397–402, 2003.
46. B. Ding, C. Li, M. Zhang, F. Ji, and X. Dong, "Effects of pore size distribution and coordination number on the prediction of filtration coefficients for straining from percolation theory," *Chem. Eng. Sci.*, vol. 127, pp. 40–51, 2015.
47. L. Liu, N. H. Loh, B. Y. Tay, S. B. Tor, Y. Murakoshi, and R. Maeda, "Effects of thermal debinding on surface roughness in micro powder injection molding," *Mater. Lett.*, vol. 61, no. 3, pp. 809–812, 2007.
48. A. T. Sidambe, I. A. Figueroa, H. G. C. Hamilton, and I. Todd, "Metal injection moulding of CP-Ti components for biomedical applications," *J. Mater. Process. Technol.*, vol. 212, no. 7, pp. 1591–1597, 2012.
49. J. L. Fan, Y. Han, T. Liu, H. C. Cheng, Y. Gao, and J. M. Tian, "Influence of surfactant addition on rheological behaviors of injection-molded ultrafine 98W-1Ni-1Fe suspension," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 23, no. 6, pp. 1709–1717, 2013.

50. T. Tadros, "Polymeric surfactants in disperse systems," *Adv. Colloid Interface Sci.*, vol. 147–148, no. C, pp. 281–299, 2009.
51. M. A. Omar and I. Subuki, "Sintering Characteristics of Injection Moulded 316L Component Using Palm-Based Biopolymer Binder," in *Sintering-Methods and Products*, no. 2012, V. Shatokha, Ed. InTech, 2012, pp. 127–146.
52. P. Wongpanit, S. Khanthsri, S. Puengboonsri, and A. Manonukul, "Effects of acrylic acid-grafted HDPE in HDPE-based binder on properties after injection and debinding in metal injection molding," *Mater. Chem. Phys.*, vol. 147, no. 1–2, pp. 238–246, 2014.
53. X. C. Xie, C. G. Lin, C. C. Jia, and R. J. Cao, "Effects of process parameters on quality of ultrafine WC/12Co injection molded compacts," *Int. J. Refract. Met. Hard Mater.*, vol. 48, pp. 305–311, 2015.
54. G. Chen, P. Cao, G. Wen, N. Edmonds, and Y. Li, "Using an agar-based binder to produce porous NiTi alloys by metal injection moulding," *Intermetallics*, vol. 37, pp. 92–99, 2013.
55. J. Meng, N. H. Loh, B. Y. Tay, G. Fu, and S. B. Tor, "Tribological behavior of 316L stainless steel fabricated by micro powder injection molding," *Wear*, vol. 268, no. 7–8, pp. 1013–1019, 2010.
56. Z. Y. Liu, N. H. Loh, K. A. Khor, and S. B. Tor, "Mechanical alloying of TiC/M2 high speed steel composite powders and sintering investigation," *Mater. Sci. Eng. A*, vol. 311, no. 1–2, pp. 13–21, 2001.
57. W. W. Yang, K. Y. Yang, and M. H. Hon, "Effects of PEG molecular weights on rheological behavior of alumina injection molding feedstocks," *Mater. Chem. Phys.*, vol. 78, no. 2, pp. 416–424, 2003.
58. J. W. Nicholson, *The Chemistry of Polymers*, Third. RSC Publishing, 2006.
59. R. M. German and A. Bose, *Injection Molding of Metals and Ceramics*. Metal powders Industries Federation, 1997.
60. S. Ahn, C. J. Hwang, Y. S. Kwon, S. J. Park, and R. M. German, "Development of ultrasonic dental tips by powder injection molding," *Int. J. Powder Metall.*, vol. 48, no. 2, pp. 11–20, 2012.
61. M. H. Ismail, R. Goodall, H. A. Davies, and I. Todd, "Porous NiTi alloy by metal injection moulding/sintering of elemental powders: Effect of sintering temperature," *Mater. Lett.*, vol. 70, pp. 142–145, 2012.

62. J. González-gutiérrez, G. B. Stringari, and I. Emri, "Powder Injection Molding of Metal and Ceramic Parts, Some Critical Issues for Injection Molding," in *Some Critical Issues for Injection Molding*, 2012, pp. 65–88.
63. V. Demers, S. Turenne, and O. Scalzo, "Segregation measurement of powder injection molding feedstock using thermogravimetric analysis, pycnometer density and differential scanning calorimetry techniques," *Adv. Powder Technol.*, vol. 26, pp. 997–1004, 2014.
64. R. DeMatteo, "Chemical exposure and plastics production : issues for women's health-A Review of literature," *National Network on Environments and Women's Health*, no. December, 2011.
65. J. Thomas L, "Gaseous Emissions and Toxic Hazards Associated with Plastics in Fire Situations -A Literature Review," 1974.
66. K. S. Weil, E. A. Nyberg, and K. L. Simmons, "Use of a Naphthalene-Based Binder in Injection Molding Net-Shape Titanium Components of Controlled Porosity," *Mater. Trans.*, vol. 46, no. 7, pp. 1525–1531, 2005.
67. K. Scott Weil, E. Nyberg, and K. Simmons, "A new binder for powder injection molding titanium and other reactive metals," *J. Mater. Process. Technol.*, vol. 176, no. 1–3, pp. 205–209, 2006.
68. T. H. Kwon and S. Y. Ahn, "Slip characterization of powder/binder mixtures and its significance in the filling process analysis of powder injection molding," *Powder Technol.*, vol. 85, no. 1, pp. 45–55, 1995.
69. Z. Y. Liu *et al.*, "Injection molding of 316L stainless steel microstructures," *Microsyst. Technol.*, vol. 9, no. 6–7, pp. 507–510, 2003.
70. Z. Y. Liu, N. H. Loh, S. B. Tor, K. A. Khor, Y. Murakoshi, and R. Maeda, "Binder system for micropowder injection molding," *Mater. Lett.*, vol. 48, no. 1, pp. 31–38, 2001.
71. J. Cheng, L. Wan, Y. Cai, J. Zhu, P. Song, and J. Dong, "Fabrication of W–20wt.%Cu alloys by powder injection molding," *J. Mater. Process. Technol.*, vol. 210, pp. 137–142, 2010.
72. H. Youhua, L. Yimin, H. Hao, L. Jia, and T. Xiao, "Preparation and Mechanical Properties of Inconel718 Alloy by Metal Injection Molding," *Rare Met. Mater. Eng.*, vol. 39, no. 5, pp. 775–780, 2010.

73. Y. Li, L. Li, and K. a. A. Khalil, "Effect of powder loading on metal injection molding stainless steels," *J. Mater. Process. Technol.*, vol. 183, no. 2–3, pp. 432–439, Mar. 2007.
74. H. Zhang, X. He, X. Qu, and L. Zhao, "Microstructure and mechanical properties of high Nb containing TiAl alloy parts fabricated by metal injection molding," *Mater. Sci. Eng. A*, vol. 526, no. 1–2, pp. 31–37, 2009.
75. N. H. M. Nor, N. Muhamad, M. Ruzi, M. H. I. Ibrahim, and K. R. Jamaludin, "Optimisation of Injection Molding Parameter of Ti-6Al-4V Powder Mix With Palm Stearin and Polyethylene for The Highest Green Strength by Using Taguchi Method," *Int. J. Mech. Mater. Eng.*, vol. 6, no. 1, pp. 126–132, 2011.
76. N. H. M. Nor, N. Muhamad, A. K. Ariffm, M. Ruzi, K. R. Jamaludin, and A. Sufizar, "Injection molding parameter optimization of titanium alloy powder mix with palm stearin and polyethylene for multiple performance using grey relational analysis," *Journal of Applied Sciences*, vol. 11, no. 10. pp. 1833–1838, 2011.
77. G. Chen, P. Cao, G. Wen, and N. Edmonds, "Debinding behaviour of a water soluble PEG/PMMA binder for Ti metal injection moulding," *Mater. Chem. Phys.*, vol. 139, no. 2–3, pp. 557–565, 2013.
78. M. E. Sotomayor, A. Várez, and B. Levenfeld, "Influence of powder particle size distribution on rheological properties of 316L powder injection moulding feedstocks," *Powder Technol.*, vol. 200, no. 1–2, pp. 30–36, Jun. 2010.
79. M. A. Omar, I. Subuki, N. Abdullah, and M. F. Ismail, "The Influence Of Palm Stearin Content On The Rheological Behaviour Of 316L Stainless Steel MIM Compact," *J. Sci. Technol.*, vol. 2, no. 2, pp. 1–14, 2010.
80. L. Liu, X. L. Ni, H. Q. Yin, and X. H. Qu, "Mouldability of various zirconia micro gears in micro powder injection moulding," *J. Eur. Ceram. Soc.*, vol. 35, no. 1, pp. 171–177, 2015.
81. A. Fayyaz, N. Muhamad, A. B. Sulong, H. S. Yunn, S. Y. M. Amin, and J. Rajabi, "Micro-powder injection molding of cemented tungsten carbide: Feedstock preparation and properties," *Ceram. Int.*, vol. 41, no. 3, pp. 3605–3612, 2015.

82. M. A. Omar, H. A. Davies, P. F. Messer, and B. Ellis, "The influence of PMMA content on the properties of 316L stainless steel MIM compact," *J. Mater. Process. Technol.*, vol. 113, no. 1–3, pp. 477–481, 2001.
83. M. Ibrahim and N. Muhamad, "Single performance optimization of micro metal injection molding for the highest green strength by using Taguchi method," *Int. J. Integr. Eng.*, no. C, pp. 35–44, 2010.
84. M. D. Hayat, G. Wen, M. F. Zulkifli, and P. Cao, "Effect of PEG molecular weight on rheological properties of Ti-MIM feedstocks and water debinding behaviour," *Powder Technol.*, vol. 270, no. Part A, pp. 296–301, 2015.
85. N. Chuankrerkkul, P. F. Messer, and H. A. Davies, "Application of polyethylene glycol and polymethyl methacrylate as a binder for powder injection moulding of hardmetals," *Chiang Mai J. Sci.*, vol. 35, no. 1, pp. 188–195, 2008.
86. M. H. . Ibrahim, "Optimization of MicroMetal Injection Moulding Parameter by Design of Experiment Method," Universiti Kebangsaan Malaysia, 2011.
87. C. Quinard, J. Song, T. Barriere, and J. C. Gelin, "Elaboration of PIM feedstocks with 316L fine stainless steel powders for the processing of micro-components," *Powder Technol.*, vol. 208, no. 2, pp. 383–389, 2011.
88. C. Quinard, T. Barriere, and J. C. Gelin, "Development and property identification of 316L stainless steel feedstock for PIM and μ PIM," *Powder Technol.*, vol. 190, no. 1–2, pp. 123–128, 2009.
89. V. P. Onbattuvelli, R. Chinn, R. K. Enneti, S. J. Park, and S. V. Atre, "The effects of nanoparticle addition on binder removal from injection molded silicon carbide," *Ceram. Int.*, vol. 40, no. 9 PART A, pp. 13861–13868, 2014.
90. G. Aggarwal, S. J. Park, I. Smid, and R. M. German, "Master decomposition curve for binders used in powder injection molding," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 38, no. 3, pp. 606–614, 2007.
91. S.-J. Park, Y. Wu, D. F. Heaney, X. Zou, G. Gai, and R. M. German, "Rheological and thermal debinding behaviors in titanium powder injection molding," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 40, no. 1, pp. 215–222, 2009.

92. C. Karatas, A. Kocer, H. I. Ünal, and S. Saritas, "Rheological properties of feedstocks prepared with steatite powder and polyethylene-based thermoplastic binders," *J. Mater. Process. Technol.*, vol. 152, no. 1, pp. 77–83, 2004.
93. V. A. Krauss, A. A. M. Oliveira, A. N. Klein, H. A. Al-Qureshi, and M. C. Fredel, "A model for PEG removal from alumina injection moulded parts by solvent debinding," *J. Mater. Process. Technol.*, vol. 182, no. 1–3, pp. 268–273, 2007.
94. J. Hidalgo, J. P. Fernández-Blázquez, A. Jiménez-Morales, T. Barriere, J. C. Gelin, and J. M. Torralba, "Effect of the particle size and solids volume fraction on the thermal degradation behaviour of Invar 36 feedstocks," *Polym. Degrad. Stab.*, vol. 98, no. 12, pp. 2546–2555, 2013.
95. J. Hidalgo, C. Abajo, A. Jiménez-Morales, and J. M. Torralba, "Effect of a binder system on the low-pressure powder injection moulding of water-soluble zircon feedstocks," *J. Eur. Ceram. Soc.*, vol. 33, no. 15–16, pp. 3185–3194, 2013.
96. M. T. Zaky, F. S. Soliman, and A. S. Farag, "Influence of paraffin wax characteristics on the formulation of wax-based binders and their debinding from green molded parts using two comparative techniques," *J. Mater. Process. Technol.*, vol. 209, no. 18–19, pp. 5981–5989, 2009.
97. W.-K. You, J.-P. Choi, S.-M. Yoon, and J.-S. Lee, "Low temperature powder injection molding of iron micro-nano powder mixture," *Powder Technol.*, vol. 228, pp. 199–205, 2012.
98. M. E. Sotomayor, B. Levenfeld, and A. Várez, "Powder injection moulding of premixed ferritic and austenitic stainless steel powders," *Mater. Sci. Eng. A*, vol. 528, no. 9, pp. 3480–3488, 2011.
99. D. Li, H. Hou, Z. Tan, and K. Lee, "Metal injection molding of pure molybdenum," *Adv. Powder Technol.*, vol. 20, no. 5, pp. 480–487, 2009.
100. W. J. Tseng, "Influence of surfactant on rheological behaviors of injection-molded alumina suspensions," *Mater. Sci. Eng. A*, vol. 289, no. 1–2, pp. 116–122, Sep. 2000.
101. S. Ahn *et al.*, "Effect of powders and binders on material properties and molding parameters in iron and stainless steel powder injection molding process," *Powder Technol.*, vol. 193, no. 2, pp. 162–169, Jul. 2009.

102. A. R. Norizzah, M. Norsyamimi, O. Zaliha, K. N. Azimah, and M. F. S. Hazirah, "Physicochemical properties of palm oil and palm kernel oil blend fractions after interesterification," *Int. Food Res. J.*, vol. 22, no. 4, pp. 1390–1395, 2014.
103. M. A. Omar, K. Noorsal, I. Subuki, N. Abdullah, and A. H. Zulkifly, "Fabrication of Metallic Implants Using Palm Based Binder Through MIM Process," *Euro PM2011*, 2011.
104. W. J. Tseng, D. M. Liu, and C. K. Hsu, "Influence of stearic acid on suspension structure and green microstructure of injection-molded zirconia ceramics," *Ceram. Int.*, vol. 25, no. 2, pp. 191–195, 1999.
105. Y. LI, X. Liu, F. Luo, and J. YUE, "Effects of surfactant on properties of MIM feedstock," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 17, no. 1, pp. 1–8, 2007.
106. E. Hryha, H. Borgstr??m, K. Sterky, and L. Nyborg, "Influence of the steel powder type and processing parameters on the debinding of PM compacts with gelatin binder," *J. Therm. Anal. Calorim.*, vol. 118, no. 2, pp. 695–704, 2014.
107. M. J. Montefrio, T. Xinwen, and J. P. Obbard, "Recovery and pre-treatment of fats, oil and grease from grease interceptors for biodiesel production," *Appl. Energy*, vol. 87, no. 10, pp. 3155–3161, 2010.
108. F. Ma and M. A. Hanna, "Biodiesel production: a review 1," *Bioresour. Technol.*, vol. 70, no. 2, pp. 1–15, 1999.
109. J. B. Williams, C. Clarkson, C. Mant, A. Drinkwater, and E. May, "Fat, oil and grease deposits in sewers: Characterisation of deposits and formation mechanisms," *Water Res.*, vol. 46, no. 19, pp. 6319–6328, 2012.
110. A. M. E. Ragauskas, Y. Pu, and A. J. Ragauskas, "Biodiesel from grease interceptor to gas tank," *Energy Sci. Eng.*, vol. 1, no. 1, pp. 42–52, 2013.
111. I. B. Banković-Ilić, I. J. Stojković, O. S. Stamenković, V. B. Veljkovic, and Y. T. Hung, "Waste animal fats as feedstocks for biodiesel production," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 238–254, 2014.
112. D. Kargbo, "Biodiesel production from municipal sewage sludges," *Energy & Fuels*, vol. 24, no. 5, pp. 2791–2794, 2010.

113. T. Kobayashi, H. Kuramochi, K. Maeda, T. Tsuji, and K. Xu, "Dual-fuel production from restaurant grease trap waste: Bio-fuel oil extraction and anaerobic methane production from the post-extracted residue," *Bioresour. Technol.*, vol. 169, pp. 134–142, 2014.
114. B. N. Mukund, B. Hausnerova, and T. S. Shivashankar, "Development of 17-4PH stainless steel bimodal powder injection molding feedstock with the help of interparticle spacing/lubricating liquid concept," *Powder Technol.*, vol. 283, pp. 24–31, 2015.
115. T. Zhang, S. Blackburn, and J. Bridgwater, "Debinding and sintering defects from particle orientation in ceramic injection moulding," *J. Mater. Sci.*, vol. 31, no. 22, pp. 5891–5896, 1996.
116. S. M. Olhero and J. M. F. Ferreira, "Influence of particle size distribution on rheology and particle packing of silica-based suspensions," *Powder Technol.*, vol. 139, no. 1, pp. 69–75, 2004.
117. B. Hausnerova, T. Sedlacek, P. Filip, and P. Saha, "The effect of powder characteristics on pressure sensitivity of powder injection moulding compounds," *Powder Technol.*, vol. 206, no. 3, pp. 209–213, 2011.
118. J. Meng, N. H. Loh, G. Fu, B. Y. Tay, and S. B. Tor, "Micro powder injection moulding of alumina micro-channel part," *J. Eur. Ceram. Soc.*, vol. 31, no. 6, pp. 1049–1056, 2011.
119. U. M. Attia and J. R. Alcock, "A review of micro-powder injection moulding as a microfabrication technique," *J. Micromechanics Microengineering*, vol. 21, no. 4, pp. 1–22, 2011.
120. S. Md Ani, A. Muchtar, N. Muhamad, and J. A. Ghani, "Fabrication of zirconia-toughened alumina parts by powder injection molding process: Optimized processing parameters," *Ceram. Int.*, vol. 40, no. 1 PART A, pp. 273–280, 2014.
121. F. Liu and K. Chou, "Determining critical ceramic powder volume concentration from viscosity measurements," vol. c, pp. 159–164, 2000.
122. M. T. Vieira, A. G. Martins, F. M. Barreiros, M. Matos, and J. M. Castanho, "Surface modification of stainless steel powders for microfabrication," *J. Mater. Process. Technol.*, vol. 1, pp. 651–656, 2007.

123. J. Hidalgo, A. Jiménez-Morales, and J. M. Torralba, "Torque rheology of zircon feedstocks for powder injection moulding," *J. Eur. Ceram. Soc.*, vol. 32, no. 16, pp. 4063–4072, 2012.
124. G. Aggarwal, S. J. Park, and I. Smid, "Development of niobium powder injection molding: Part I. Feedstock and injection molding," *Int. J. Refract. Met. Hard Mater.*, vol. 24, no. 3, pp. 253–262, 2006.
125. X. quan LIU, Y. min LI, J. ling YUE, and F. hua LUO, "Deformation behavior and strength evolution of MIM compacts during thermal debinding," *Trans. Nonferrous Met. Soc. China (English Ed.)*, vol. 18, no. 2, pp. 278–284, 2008.
126. M. Belgacem, B. Thierry, and G. Jean-Claude, "Investigations on thermal debinding process for fine 316L stainless steel feedstocks and identification of kinetic parameters from coupling experiments and finite element simulations," *Powder Technol.*, vol. 235, pp. 192–202, 2013.
127. L. I. Song-lin *et al.*, "Effects of sintering atmosphere on the microstructure and mechanical property of sintered 316L stainless steel," *J. Cent. South Univ. Tecnol.*, vol. 10, no. 1, pp. 1–6, 2003.
128. M. H. Ismail, I. Subuki, M. A. Omar, I. Todd, and H. a Davies, "Properties of MIM Gas-Atomized 316L Stainless Steel using a Palm Stearin Developed in Malaysia," *Euro PM2008*, no. October, pp. 269–275, 2008.
129. K. . Hwang, G. J. Shu, and H.J Lee, "Solvent Debinding Behavior of Powder Injection Molded Components Prepared from Powders with Different Particle Sizes," *Metall. Metarials Trans.*, vol. 36A, no. January, p. 161, 2005.
130. L. Liu, N. H. Loh, B. Y. Tay, S. B. Tor, Y. Murakoshi, and R. Maeda, "Mixing and characterisation of 316L stainless steel feedstock for micro powder injection molding," *Mater. Charact.*, vol. 54, pp. 230–238, 2005.
131. B. Y. Tay, N. H. Loh, S. B. Tor, F. L. Ng, G. Fu, and X. H. Lu, "Characterisation of micro gears produced by micro powder injection moulding," *Powder Technol.*, vol. 188, no. 3, pp. 179–182, 2009.
132. B. Y. Tay, L. Liu, N. H. Loh, S. B. Tor, Y. Murakoshi, and R. Maeda, "Characterization of metallic micro rod arrays fabricated by μ MIM," *Mater. Charact.*, vol. 57, no. 2, pp. 80–85, 2006.

133. G. J. Shu, K. S. Hwang, and Y. T. Pan, "Improvements in sintered density and dimensional stability of powder injection-molded 316L compacts by adjusting the alloying compositions," *Acta Mater.*, vol. 54, no. 5, pp. 1335–1342, 2006.
134. P. Suri, R. P. Koseski, and R. M. German, "Microstructural evolution of injection molded gas- and water-atomized 316L stainless steel powder during sintering," *Mater. Sci. Eng. A*, vol. 402, no. 1–2, pp. 341–348, 2005.
135. R. Zauner, C. Binet, D. F. Heaney, and J. Piemme, "Variability of feedstock viscosity and its correlation with dimensional variability of green powder injection moulded components," *Powder Metall.*, vol. 47, no. 2, pp. 150–155, 2004.
136. H. Abolhasani and N. Muhamad, "A new starch-based binder for metal injection molding," *J. Mater. Process. Technol.*, vol. 210, no. 6–7, pp. 961–968, 2010.
137. M. R. Raza, F. Ahmad, M. A. Omar, and R. M. German, "Binder Removal from Powder Injection Molded 316L Stainless Steel," *J. Appl. Sci.*, vol. 11, no. 11, pp. 2042–2047, 2011.
138. J.-P. Choi, H.-G. Lyu, W.-S. Lee, and J.-S. Lee, "Investigation of the rheological behavior of 316L stainless steel micro-nano powder feedstock for micro powder injection molding," *Powder Technol.*, vol. 261, no. April, pp. 201–209, 2014.
139. S.-H. Ko, W. Lee, J. M. Jang, and J.-S. Seo, "Effects of debinding and sintering atmosphere in microstructure of micro MIMed part," *Proc. World Powder Metall. Congr. Exhib. World PM 2010*, vol. 1, no. 3, p. 478, 2010.
140. W. Fang, X. He, R. Zhang, S. Yang, and X. Qu, "The effects of filling patterns on the powder-binder separation in powder injection molding," *Powder Technol.*, vol. 256, pp. 367–376, 2014.
141. M. H. . Ibrahim, N. Muhamad, and A. B. Sulong, "Rheological Investigation of Water Atomised Stainless Steel Powder for Micro Metal Injection Molding," *Int. J. Mech. Mater. Eng.*, vol. 4, no. 1, pp. 1–8, 2009.
142. U. M. Attia, M. Hauata, I. Walton, D. Annicchiarico, and J. R. Alcock, "Creating movable interfaces by micro-powder injection moulding," *J. Mater. Process. Technol.*, vol. 214, no. 2, pp. 295–303, 2014.

143. D. Li, H. Hou, L. Liang, and K. Lee, "Powder injection molding 440C stainless steel," *Int. J. Adv. Manuf. Technol.*, vol. 49, pp. 105–110, 2010.
144. N. H. M. Nor, N. Muhamad, A. K. A. M. Ihsan, and K. R. Jamaludin, "Sintering parameter optimization of Ti-6Al-4V metal injection molding for highest strength using palm stearin binder," *Procedia Eng.*, vol. 68, pp. 359–364, 2013.
145. D.-M. Liu and W. J. Tseng, "Influence of debinding rate, solid loading and binder formulation on the green microstructure and sintering behaviour of ceramic injection mouldings," *Ceram. Int.*, vol. 24, no. 6, pp. 471–481, 1998.
146. W. J. Tseng and C.-K. K. Hsu, "Cracking defect and porosity evolution during thermal debinding in ceramic injection moldings," *Ceram. Int.*, vol. 25, no. 5, pp. 461–466, Jul. 1999.
147. M. T. Zaky, "Effect of solvent debinding variables on the shape maintenance of green molded bodies," *J. Mater. Sci.*, vol. 39, no. 10, pp. 3397–3402, 2004.
148. N. H. Loh, S. B. Tor, and K. A. Khor, "Production of metal matrix composite part by powder injection molding," *J. Mater. Process. Technol.*, vol. 108, no. 3, pp. 398–407, 2001.
149. Z. Y. Liu, N. H. Loh, K. A. Khor, and S. B. Tor, "Sintering activation energy of powder injection molded 316L stainless steel," *Scr. Mater.*, vol. 44, no. 7, pp. 1131–1137, 2001.
150. P. C. Yu, Q. F. Li, J. Y. H. Fuh, T. Li, and L. Lu, "Two-stage sintering of nano-sized yttria stabilized zirconia process by powder injection moulding," *J. Mater. Process. Technol.*, vol. 192–193, pp. 312–318, 2007.
151. A. C. Gonçalves, "Metallic powder injection molding using low pressure," *J. Mater. Process. Technol.*, vol. 118, no. 1–3, pp. 193–198, 2001.
152. H. Jorge, C. Technology, G. Industry, R. C. V. Simão, and A. M. Cunha, "Metal Injection Moulding Using a Water-Soluble Binder : Effect of The Back-Bone Polymer in the Process," *Euro PM2008*, pp. 231–238, 2008.
153. Z. Y. Liu, N. H. Loh, S. B. Tor, and K. A. Khor, "Characterization of powder injection molding feedstock," *Mater. Charact.*, vol. 49, no. 4, pp. 313–320, 2003.
154. J. Bricout, J.-C. Gelin, C. Ablitzer, P. Matheron, and M. Brothier, "Influence of powder characteristics on the behaviour of PIM feedstock," *Chem. Eng. Res. Des.*, vol. 91, no. 12, pp. 2484–2490, Mar. 2013.

155. M. Belgacem, B. Thierry, and G. Jean-Claude, "Investigations on thermal debinding process for fine 316L stainless steel feedstocks and identification of kinetic parameters from coupling experiments and finite element simulations," *Powder Technol.*, vol. 235, pp. 192–202, 2013.
156. M. Sahli, J. Gelin, and T. Barriere, "Characterisation and replication of metallic microfluidic devices using three different powders processed by hot embossing," *Powder Technol.*, vol. 246, pp. 284–302, 2013.
157. J. P. Choi, G. Y. Lee, J. Il Song, W. S. Lee, and J. S. Lee, "Sintering behavior of 316L stainless steel micro-nanopowder compact fabricated by powder injection molding," *Powder Technol.*, vol. 279, pp. 196–202, 2015.
158. T. S. Shivashankar, R. K. Enneti, S.-J. Park, R. M. German, and S. V. Atre, "The effects of material attributes on powder-binder separation phenomena in powder injection molding," *Powder Technol.*, vol. 243, pp. 79–84, 2013.
159. D.-F. Lii, J.-L. Huang, C.-H. Lin, and H.-H. Lu, "The effects of atmosphere on the thermal debinding of injection moulded Si₃N₄ components," *Ceram. Int.*, vol. 24, no. 2, pp. 99–104, 1998.
160. B. Mamen, T. Barriere, and J.-C. Gelin, "Study of the Thermal Decomposition for Different Feedstocks Powder Injection Moulding," *Euro PM2011*, 2011.
161. L. Song-lin, L. Yi-min, Q. Xuan-hui, and H. Bar-yun, "Rheological properties for MIM feedstock," *Trans Nonferrous Met. Soc. China*, vol. 12, no. 1, pp. 105–108, 2002.
162. E. Saldivar-Guerra and E. Vivaldo-Lima, *Handbook of Polymer Synthesis, Characterization, and Processing*. John Wiley & Sons, Inc., 2013.
163. W.-W. Yang, K.-Y. Yang, and M.-H. Hon, "Effects of PEG molecular weights on rheological behavior of alumina injection molding feedstocks," *Mater. Chem. Phys.*, vol. 78, pp. 416–424, 2002.
164. I. Agote, A. Odriozola, M. Gutierrez, A. Santamarı, and J. Quintanilla, "Rheological study of waste porcelain feedstocks for injection moulding," *J. Eur. Ceram. Soc.*, vol. 21, pp. 2843–2853, 2001.
165. D.-M. Liu, "Effect of Dispersants on the Rheological Behavior of Zirconia-Wax Suspensions," *J. Am. Ceram. Soc.*, vol. 82, no. 5, pp. 1162–1168, 1999.

166. Z. Baojun, Q. Xuanhui, and T. Ying, "Powder injection molding of WC–8%Co tungsten cemented carbide," *Int. J. Refract. Met. Hard Mater.*, vol. 20, no. 5–6, pp. 389–394, Dec. 2002.
167. R. Supati, N. H. Loh, K. A. Khor, and S. B. Tor, "Mixing and characterization of feedstock for powder injection molding," *Mater. Lett.*, vol. 46, no. 2–3, pp. 109–114, 2000.
168. C. H. Ji, N. H. Loh, K. A. Khor, and S. B. Tor, "Sintering study of 316L stainless steel metal injection molding parts using Taguchi method: Final density," *Mater. Sci. Eng. A*, vol. 311, no. 1–2, pp. 74–82, 2001.
169. D. F. Heaney, T. W. Mueller, and P. a. Davies, "Mechanical properties of metal injection moulded 316L stainless steel using both prealloy and master alloy techniques," *Powder Metall.*, vol. 47, no. 4, pp. 367–373, 2004.
170. A. O. Yakimov and T. W. Coyle, "A statistical analysis of the factors affecting thermal debinding," *Mater. Sci. Lett.*, vol. 19, pp. 2255–2257, 2000.
171. H. Jorge, L. Hennetier, A. Correia, and A. Cunha, "Tailoring Solvent / Thermal Debinding 316L Stainless Steel Feedstocks for PIM : An Experimental Approach," *Euro PM2005*, pp. 351–357, 2005.
172. N. H. Loh and R. M. German, "Statistical analysis of shrinkage variation for powder injection molding," *J. Mater. Process. Technol.*, vol. 59, no. 3 SPEC. ISS., pp. 278–284, 1996.
173. S. V Atre, S. Park, R. Zauner, and R. M. German, "Process simulation of powder injection moulding : identification of significant parameters during mould filling phase," *Powder Metall.*, vol. 50, no. 1, 2007.
174. K. Lee *et al.*, "Gas-assisted powder injection molding : A study on the effect of processing variables on gas penetration," *Powder Technol.*, vol. 200, no. 3, pp. 128–135, 2010.
175. S. W. Lee *et al.*, "Effects of process parameters in plastic, metal, and ceramic injection molding processes," *Korea Aust. Rheol. J.*, vol. 23, no. 3, pp. 127–138, 2011.
176. Y. Li, F. Jiang, L. Zhao, and B. Huang, "Critical thickness in binder removal process for injection molded compacts," *Mater. Sci. Eng. A*, vol. 362, no. 1–2, pp. 292–299, 2003.

177. S. W. Kim, H. Lee, H. Song, B. H. Kim, and B. H. Kima, "Pore Structure Evolution During Solvent Extraction and Wicking," *Ceram. Int.*, vol. 22, no. 95, pp. 7–14, 1996.
178. S. W. Kim, H. W. Lee, and H. Song, "Effect of minor binder on capillary structure evolution during wicking," *Ceram. Int.*, vol. 25, no. 7, pp. 671–676, 1999.
179. L. Gorjan, T. Kosmač, and A. Dakskobler, "Single-step wick-debinding and sintering for powder injection molding," *Ceram. Int.*, vol. 40, pp. 887–891, 2014.
180. R. K. Enneti, T. S. Shivashankar, S. J. Park, R. M. German, and S. V. Atre, "Master debinding curves for solvent extraction of binders in powder injection molding," *Powder Technol.*, vol. 228, pp. 14–17, 2012.
181. D.-S. S. Tsai and W.-W. W. Chen, "Solvent debinding kinetics of alumina green bodies by powder injection molding," *Ceram. Int.*, vol. 21, no. 4, pp. 257–264, Jan. 1995.
182. T. S. Shivashankar and R. M. German, "Effective Length Scale for Predicting Solvent-Debinding Times of Components Produced by Powder Injection Molding," *J. Am. Ceram. Soc.*, vol. 82, no. 5, pp. 1146–1152, 1999.
183. B.-J. Zhu, X.-H. Qu, and Y. Tao, "A novel binder and binder extraction method for powder injection molding of tungsten cemented carbide .," *Trans Nonferrous Met. Soc. China*, vol. 13, no. 2, pp. 262–266, 2003.
184. R. V. B. Oliveira, V. Soldi, M. C. Fredel, and A. T. N. Pires, "Ceramic injection moulding: Influence of specimen dimensions and temperature on solvent debinding kinetics," *J. Mater. Process. Technol.*, vol. 160, no. 2, pp. 213–220, 2005.
185. K. S. S. Hwang, G. J. J. Shu, and H. J. J. Lee, "Solvent Debinding Behavior of Powder Injection Molded Components Prepared from Powders with Different Particle Sizes," *Metall. Mater. Trans. A*, vol. 36, no. January, pp. 161–167, 2005.
186. E. J. Westcot, C. Binet, and R. M. German, "In situ dimensional change, mass loss and mechanisms for solvent debinding of powder injection moulded components," *Powder Metall.*, vol. 46, no. 1, pp. 61–67, 2003.

187. H. K. Lin and K. S. Hwang, "In situ dimensional changes of powder injection-molded compacts during solvent debinding," *Acta Mater.*, vol. 46, no. 12, pp. 4303–4309, 1998.
188. W.-W. Yang, K.-Y. Yang, M.-C. Wang, and M.-H. Hon, "Solvent debinding mechanism for alumina injection molded compacts with water-soluble binders," *Ceram. Int.*, vol. 29, no. 7, pp. 745–756, Jan. 2003.
189. H. Guoxin, Z. Lixiang, F. Yunliang, and L. Yanhong, "Fabrication of high porous NiTi shape memory alloy by metal injection molding," *J. Mater. Process. Technol.*, vol. 206, no. 1–3, pp. 395–399, 2008.
190. Y. Thomas and B. R. Marple, "Partially Water-Soluble Binder Formulation for Injection Molding Submicrometer Zirconia," *Advanced Performance Materials*, vol. 41, no. 5, pp. 25–41, 1998.
191. H. Ö. Gülsøy and Ç. Karataş, "Development of poly(2-ethyl-2-oxaline) based water-soluble binder for injection molding of stainless steel powder," *Mater. Des.*, vol. 28, no. 9, pp. 2488–2491, 2007.
192. G. J. Yang, C. J. Li, S. Q. Fan, and J. C. Gao, "Influence of pore structure on ion diffusion property in porous TiO₂ coating and photovoltaic performance of dye-sensitized solar cells," *Surf. Coatings Technol.*, vol. 205, no. 10, pp. 3205–3210, 2011.
193. I. D. Jung, J. M. Park, J. H. Yu, T. G. Kang, S. J. Kim, and S. J. Park, "Particle size effect on the magneto-rheological behavior of powder injection molding feedstock," *Mater. Charact.*, vol. 94, pp. 19–25, 2014.
194. S. Banerjee and C. J. Joens, "7 - Debinding and sintering of metal injection molding (MIM) components," in *Handbook of Metal Injection Moulding*, no. Mim, 2012, pp. 133–180.
195. I. Majewsaka-Glabus, L. Zhuang, R. Vetter, and J. Duszczycy, "Thermal debinding of Fe₃Al-X metal powder compacts," *J. Mater. Sci.*, vol. 30, pp. 6209–6217, 1995.
196. M. Trunec and J. Cihlář, "Thermal debinding of injection moulded ceramics," *J. Eur. Ceram. Soc.*, vol. 17, no. 2–3, pp. 203–209, 1997.
197. L. Liu, N. H. Loh, B. Y. Tay, and S. B. Tor, "Microstructure evolution of 316L stainless steel micro components prepared by micro powder injection molding," *Powder Technol.*, vol. 206, no. 3, pp. 246–251, 2011.

198. O. Ertugrul, H.-S. Park, K. Onel, and M. Willert-Porada, “Effect of particle size and heating rate in microwave sintering of 316L stainless steel,” *Powder Technol.*, vol. 253, pp. 703–709, 2014.
199. E. Klar and P. K. Samal, *Powder Metallurgy Stainless Steel-Processing, Microstructure and Properties*, First prin. 2007.
200. Y. Wu, R. M. German, D. Blaine, B. Marx, and C. Schlaefer, “Effects of residual carbon content on sintering shrinkage, microstructure and mechanical properties of injection molded 17-4 PH stainless steel,” *J. Mater. Sci.*, vol. 37, no. 17, pp. 3573–3583, 2002.
201. A. Várez, B. Levenfeld, J. M. Torralba, G. Matula, and L. A. Dobrzanski, “Sintering in different atmospheres of T15 and M2 high speed steels produced by a modified metal injection moulding process,” *Mater. Sci. Eng. A*, vol. 366, no. 2, pp. 318–324, 2004.
202. A. Simchi, A. Rota, and P. Imgrund, “An investigation on the sintering behavior of 316L and 17-4PH stainless steel powders for graded composites,” *Mater. Sci. Eng. A*, vol. 424, no. 1–2, pp. 282–289, 2006.
203. R. P. Koseski, P. Suri, N. B. Earhardt, R. M. German, and Y.-S. Kwon, “Microstructural evolution of injection molded gas- and water-atomized 316L stainless steel powder during sintering,” *Mater. Sci. Eng. A*, vol. 390, no. 1–2, pp. 171–177, 2005.
204. G. Fu, N. H. Loh, S. B. Tor, B. Y. Tay, Y. Murakoshi, and R. Maeda, “Injection molding, debinding and sintering of 316L stainless steel microstructures,” *Appl. Phys. A Mater. Sci. Process.*, vol. 81, no. 3, pp. 495–500, 2005.
205. M. H. I. Ibrahim, “Kajian Pengoptimuman Parameter Pengacuan Suntikan Logam Mikro Dengan Menggunakan Rekabentuk Eksperimen,” Universiti Kebangsaan Malaysia, 2011.
206. Z. Ma, D. Chen, J. Gu, B. Bao, and Q. Zhang, “Determination of pyrolysis characteristics and kinetics of palm kernel shell using TGA-FTIR and model-free integral methods,” *Energy Convers. Manag.*, vol. 89, pp. 251–259, 2015.
207. G. Aggarwal, I. Smid, S. J. Park, and R. M. German, “Development of niobium powder injection molding. Part II: Debinding and sintering,” *Int. J. Refract. Met. Hard Mater.*, vol. 25, no. 3, pp. 226–236, 2007.

208. M. A. Ghazavi, M. Fallahipanah, and H. S. Jeshvaghani, "A feasibility study on beef tallow conversion to some esters for biodiesel production," *Int. J. Recycl. Org. Waste Agric.*, vol. 2, no. 1, p. 2, 2013.
209. J. Vlachopoulos and N. Polychronopoulos, "Basic Concepts In Polymer Melt Rheology and Their Importance In Processing," in *Applied Polymer Rheology: Polymeric Fluids with Industrial Application*, no. April, Hoboken, New Jersey, USA: John Wiley & Sons, Inc., 2015, pp. 1–26.
210. G. O. Shonaike and S. G. Advani, *Advanced polymeric materials : Structure Property Relationships*. Taylor & Francis, 2003.
211. A. M. Amin, M. Halim, I. Ibrahim, R. Asmawi, and N. Mustafa, "Effect of Solvent Debinding Variables on Green Compact With Different Binder Formulation," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 4, pp. 2442–2447, 2016.
212. D. C. Zipperian, *Metallographic Handbook*. 2011.
213. S. Y. Heng, M. R. Raza, N. Muhamad, A. B. Sulong, and A. Fayyaz, "Micro-powder injection molding (μ PIM) of tungsten carbide," *Int. J. Refract. Met. Hard Mater.*, vol. 45, pp. 189–195, 2014.
214. M. Khakbiz, a. Simchi, and R. Bagheri, "Investigation of rheological behaviour of 316L stainless steel-3 wt-%TiC powder injection moulding feedstock," *Powder Metall.*, vol. 48, no. 2, pp. 144–150, 2005.
215. G. Thavanayagam, K. L. Pickering, J. E. Swan, and P. Cao, "Analysis of rheological behaviour of titanium feedstocks formulated with a water-soluble binder system for powder injection moulding," *Powder Technol.*, vol. 269, pp. 227–232, 2014.
216. B. Berginc, Z. Kampus, and B. Sustarsic, "Influence of feedstock characteristics and process parameters on properties of MIM parts made of 316L," *Powder Metall.*, vol. 50, no. 2, pp. 172–183, 2007.
217. N. H. M. Nor, N. Muhamad, M. H. I. Ibrahim, M. Ruzi, and K. R. Jamaladin, "Optimization of Injection Molding Parameter of Ti-6al-4v Powder Mix With Palm Stearin and Polyethylene for The Highest Green Strength by Using Taguchi Method," *Int. J. Mech. Mater. Eng.*, vol. 6, no. 1, pp. 126–132, 2011.

218. M. H. I. Ibrahim, N. Muhamad, A. B. Sulong, and K. R. Jamaludin, “Optimization of Micro Metal Injection Molding with Multiple Performance Characteristics using Grey Relational Grade,” *Chiang Mai J. Sci.*, vol. 38, no. 2, pp. 231–241, 2011.
219. Y. S. Zu and S. T. Lin, “Optimizing the mechanical properties of injection molded W-4 . 9 % Ni-2 . 1 % Fe in debinding,” *Mater. Process. Technol.*, vol. 6, no. 71, pp. 1–6, 1996.
220. M. . Omar, I. Subuki, N. Abdullah, and M. F. Ismail, “The influence of palm stearin content on the rheological behaviour of 316L SS MIM compact.PDF,” *J. Sci. Technol.*, vol. 2, no. 2, pp. 1–14, 2011.
221. B. McConnell and I. H. Farag, “Kinetics study of the solvent extraction of lipids from Chlorella vulgaris,” *Int. J. Eng. Tech. Res.*, vol. 1, no. 10, pp. 28–37, 2013.
222. M. Diphare and E. Muzenda, “Influence of Solvents on the Extraction of Oil from Waste Lubricating Grease : A comparative Study,” in *2nd International Conference on Agricultural, Environment and Biological Sciences (ICAEBs 2013)*, 2013, pp. 17–19.
223. C. C. Yang, S. W. Cho, and L. C. Wang, “The relationship between pore structure and chloride diffusivity from ponding test in cement-based materials,” *Mater. Chem. Phys.*, vol. 100, no. 2–3, pp. 203–210, 2006.
224. L. Shen and Z. Chen, “Critical review of the impact of tortuosity on diffusion,” *Chem. Eng. Sci.*, vol. 62, no. 14, pp. 3748–3755, 2007.
225. A. Breen, V. Milosavljević, and D. P. Dowling, “Influence of gas type on the thermal efficiency of microwave plasmas for the sintering of metal powders,” *Plasma Chem. Plasma Process.*, vol. 31, no. 5, pp. 771–785, 2011.
226. A. V. C. Sobral, M. P. Hierro, F. J. Pérez, W. Ristow Jr, and C. V. Franco, “Oxidation of injection molding 316L stainless steel at high temperature,” *Mater. Corros.*, vol. 51, no. 11, pp. 791–796, 2000.
227. H. Kotan, “Microstructural evolution of 316L stainless steels with yttrium addition after mechanical milling and heat treatment,” *Mater. Sci. Eng. A*, vol. 647, pp. 136–143, 2015.
228. B. B. HE, *Two-dimensional x-ray diffraction*. John Wiley & Sons, Inc., 2009.

229. Z. Jian and W. Hejing, "The Physical Meanings of 5 Basic Parameters for an X-Ray Diffraction Peak and Their Application *," *Chinese J. Geochemistry*, vol. 22, no. 1, 2003.

