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POWDER INJECTION MOULDING, ITS OUTSTANDING FEATURES AND DEVELOPMENT

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4.0 INTRODUCTION

Metal Injection moulding (MIM) is a development of the traditional powder metallurgy (PM) process and is rightly regarded as a branch of that technology. The standard PM process is to compact a lubricated powder mix in a rigid die by uniaxial pressure, eject the compact from the die, and sinter it. It is a novel process which combines the plastic injection moulding with the conventional powder metallurgy technology.

Quite complicated shapes can be and are regularly being produced by the million, but there is one significant limitation as regards to shape. In the MIM process, there are four processing steps: (1) mixing – compounding the metal powder and organic binder into feedstock; (2) moulding – shaping the parts from feedstock as in plastic injection moulding; (3) debinding – removing the binder in the moulded parts by pyrolysis or solvent soaking; (4) sintering –densifying the debound parts to a high final density.

The use of injection moulding for the production of quite intricate parts in a number of plastic materials has been known for many years, and most of us come into contact with them in some form or other every day. One important feature of such parts is that they are relatively cheap. However, for many engineering applications these thermo-plastic materials have quite inadequate mechanical properties. They are relatively soft, have limited strength and do not resist elevated temperatures.

Some improvement is made possible by the use of solid fillers-ceramic or metal powders-but the real breakthrough occurred when it was found out that it is possible to incorporate a very high volume fraction of metal powder in a mix so that, instead of a filled plastic part, a plastic-bonded metal or ceramic part is produced. Careful removal of the plastic binder leaves a skeleton of metal or ceramic which, although fragile, can be handled safely and sintered in much the same way as traditional die compacted parts. After sintering, densities of 95% or more are reached and the mechanical properties are, for that reason, generally superior or equivalent to those of traditional PM parts.

The major importance of the MIM process is the rheological properties of the feedstock. The rheological properties are referred to the mixing of the powder-binder.

The viscosity at the moulding temperature must be such that the mix flows smoothly into the die without any segregation, and the viscosity should be as constant as possible over a range of temperature. However, the mix must become rigid on cooling. These requirements dictate the properties of the binders used, and to some extend the granulometry of the powder.

In principle, the use of a very fine powder, with diameter less than 20µm, and a well-controlled high temperature (<melt temperature) may lead to a nearly prefect densification. Such small particle size is expensive for mass productions. Thus, to make the MIM relevant with wide range of application in industries, this research aims to study the bigger powder particles for the MIM and also to find the possibilities of mixing the bi-modal powder particles.

4.1 PROCESS DEVELOPMENT FOR COMMERCIALS

Metal injection moulding (MIM) process is fairly new as a commercial process. Its economic and technical advantages will not be available using other procedures especially since the MIM process does not involve any material waste/chips.

MIM remained relatively uncommon until the latter half of the 1970s. Its patent holders are Rivers (1976) and Wicch (1980), who were the first to apply thermal plastics to binders. [1] Dr Wicch used thermal plastics as binders with the aim of enhancing the accuracy of the powder metallurgy method, and developed a method to inject mould parts and degrease the parts by heat decomposition.

The basic metal injection moulding procedure involves blending a polymer with an extremely fine (10-20 μm) metal powder. The blended material is injection moulded using the same type of equipment and tools employed by the plastics industry. The moulded (or green) parts are placed in a low temperature oven for the initial stages of decomposition of the organic material. They are then transferred to a high temperature furnace for final polymer removal and complete sintering, using controlled temperatures and protective atmospheres.

If desired, carbon can be added at this point by methane additions to the atmosphere while the parts are still porous. Components shrink about 15 percent during the sintering operation. Parts are normally ready for use immediately after sintering, although secondary operations such as tumbling or tapping may be added.

4.2 THE OUTSTANDING FEATURES

MIM offers two major advantages over conventional powder metallurgy processing. The most obvious is three-dimensional design flexibility. In theory, any shape which can be injection moulded in plastic can also be done in metal. The mass production of injection moulded plastic toys gives the idea of design freedom.

The second important advantage is high density. Conventional structural powder metal parts are produced at densities of 75 percent to 90 percent. MIM products are typically 93 percent to 97 percent dense, which means higher strength, better corrosion resistance, and the elimination of interconnected porosity.

Because of the high density of MIM components, properties approach to those of wrought material. This means they can compete with other metal forming operations, even for demanding applications. Quantities, exact geometry and physical requirements will finally determine whether MIM is the most attractive alternative.

4.3 MIM PROCESS IMPROVEMENTS

Literature [1] shows that only four countries in the world (Japan, America, Germany and Taiwan) are aggressively conducting extensive research on the MIM.

Many research papers have been published [1-14] pertaining to the Powder Metallurgy (PM). The research area is rather new, thus research opportunities in the MIM is still wide. Authors in the literatures [2-5] are investigating about the advancement of the binder’s technology. Whilst author [6] studies on the feedstock development. Orban [7] presents research directions in the sintered part technology improvement. There are still lots of rooms in researching for

Mechanical properties improvements such as increasing powder compressibility/homogeneity, dust and hazard reduction, improvement on the die filling and lubrication processes, advanced compaction/injection methods, and advanced sintering methods. The capability of the PM in complex parts processing needs more scientific research especially in the area of MIM, Ceramics Injection Moulding (CIM), and selective laser sintering. Studies about producing large sintered parts are also necessary together with study on improving metal matrix properties.

The rheological properties of the novel binder system and feedstock have been investigated by Petzoidt, Kunze and Seidel [2] by using the capillary rheometry. The binder system based on special functional polymers and lubricants is applied for the MIM of 316L steel powders. They then compared the water and gas atomised stainless steel powder and finally found the influence of particle morphology and the variation of the powder binder ratio. The thermo analysis was used to examine mixing and moulding behaviour as well as the characteristics of the debinding process. In another research, Kunze, Hartwig and Vell [3] investigated binders for MIM titanium in order to find out whether oxidation or carburisation of the metal caused by the binder and the process can be avoided.

Binders for alumina powder have been examined by Spur and Merz [4]. They examine fourteen binders for injection moulding of alumina powder with a powder volume of 60%. In order to be able to judge the function of the examined binders, their different components were changed systematically. The wetting agent turned out to be of vital importance. It proved to be favourable to limit the polymer components to 30 % mass related to the binder to obtain an adequate flowability. They also discovered that the degradation mechanism of the polymer component has the main influence on the parts quality.

In an M. Sc. Dissertation, Saurin [5] carried out an experimental study to develop polymer binder formulations which could be used in injection moulding of metal powders. These polymer/metal compounds were then injection moulded for the evaluation of the mechanical properties of the moulded compacts. He had done detailed investigation to examine the cracking of the moulded parts and finally analysed the obtained result in terms of the difference in composition and rheology of the compounds, and the moulding conditions used.

Merz et. al. [6], studies about the development of the fine grained feedstock powders (average particle size 100-500nm) as well as appropriate binders. In the initial study, they doped 3 mol% Y_2O_3 into the fine zirconia's powders. The result shows that the feedstock with these powders may show lower viscosities allowing higher filling grades. This leads to a lower shrinkage during sintering and gives the chance to reduce shrinkage tolerances. Further, they perform another experiment with feedstock consisting of small-sized Al_2O_3 powder (0.7 μm) and using two different commercially available binders. The result shows that the microstructures with aspect ratios of five and eventually more can be realised. They concluded in their paper that, the production of microparts and microstructured part by MIM will only succeeds if all related process steps fit together perfectly. Beginning with a suitable powder, the development of optimised feedstocks is the fundamental work.

Kowalski and Duszczyk [8] reported his work on their investigation of the specific heat of the commercially available 316L BASF powder injection moulding feedstock. The investigation on several samples proved that the binder is uniformly distributed and no clustering of powder particles has been found. Six cooling scans for both the binder (without metal powder) and the feedstock (with metal powder) with different cooling rates ranging from 10-90 ^{o}C min^{-1} were performed in the research. They noticed that the cooling rate affects to a large extend the transition temperature of the molten binder material. The peak values of the specific heat decrease and the cooling rate rises. The calculated mean values of the specific heat over the 135-185 ^{o}C temperature range (processing temperature range) decrease as well with increased cooling speed. This phenomenon can be explained by the undercooling effect and consequently different level of crystallinity of the semi-crystalline binder. The study noticed that the specific heat of the powder injection moulding feedstock is lower than that of most plastics materials. Therefore the total heat load per gram of material of the PIM molten feedstock is also lower as compared to that of typical plastic materials. This fact has far reaching consequences for the cooling phenomena during PIM. The value of the specific heat for both the binder system and the PIM feedstock depend very much on the actual cooling rate during experiments. Contribution made by Kowalski and Duszczyk [8] is important for this study because the consistency of the feedstock rheology is influenced by the above studied parameters.

Johnson et.al. [9], measured the sintering shrinkage of several injection moulded materials, and the stress modal was used to predict their suitability for co-sintering defect-free components. The composition used were, M2 molybdenum high speed tool steel, 316L austenitic stainless steel, and 630 precipitation hardening stainless steel, which were produced from prealloyed powders. In the experiment, the powders for each composition were mixed with a wax-polymer binder at a solids loading of 65 volume percent. MPIF standard 50 tensile bars and demonstration components were injection moulded. The injection moulded components were debound by a two-step process. First were solvent debound for removing the wax and the second one was thermally debound and presintered by heating to 900 ^{o}C in a hydrogen atmosphere. The debound components were heated in a graphite vacuum furnace at a rate of 10^{o}C/minute to temperatures ranging from 1225^{o} to 1330 ^{o}C. The M2 tool steel samples were heat treated in nitrogen by preheating to 800 ^{o}C, hardening at 1170^{o}C for 5 minutes, air quenching, and single tempering at 550^{o}C for 1 hour. The samples were wrapped in stainless steel foil to prevent decarburisation. The intention of their study was to generate bi-material net-shape structures with multi-functional properties.

The above study is different with this proposed research, where Johnson et.al. [9] studies on the bi-material, the proposed research studies on the bi-modal particle in the MIM.

4.4 CASE STUDIES

There are also numerous case studies which experiment on the application of the MIM [10-14]. Zinelis et. al. [10] investigates the bonding base surface morphology, alloy type, microstructure, and hardness of four types of orthodontic brackets produced by MIM. The bonding base morphology of the brackets was evaluated by scanning electron microscopy (SEM). Brackets from each manufacturer were embedded in epoxy resin, and after metallographic grinding, polishing and coating were analysed by x-ray energy-dispersive spectroscopic (EDS) microanalysis to assess their elemental composition. Then, the brackets were subjected to metallographic etching to reveal their metallurgical structure. The same specimen surfaces were re-polished and used for Vickers microhardness measurements. The results were statistically analysed with one-way analysis of variance and Student-Newman-Keuls multiple comparison test at the 0.05 level of significance. The findings of SEM observations showed a great variability in the base morphology design among the brackets tested. The x-ray EDS analysis demonstrated that each bracket was manufactured from different ferrous or Co-based alloys. Metallographic analysis showed the presence of a large grain size and a much finer grain size for the Extremo bracket. Vickers hardness showed great variations among the brackets. The results of this study showed that there are significant differences in the base morphology, composition, microstructure, and microhardness among the brackets tested, which may anticipate significant clinical implications.

The powder injection moulding as a production process for microparts is very promising, because this technique allows a near net shape fabrication of microstructured parts with nearly no postprocessing steps. Many metallic and ceramic materials are available as powders. [11] Many precision components such as ceramic panel, clock parts, antenna part, printer parts, FDD head parts as well as automobile body parts can be produced by MIM. [1]

Micro powder injection moulding (μPIM) is a promising process for low cost fabrication of three-dimensional microstructures. The μPIM can be used for a wide range of metal and ceramic materials, combined with the potential for mass production. Literature [12], presents the investigation on the moulding of 316L stainless steel microstructures. Three different micro-cavity shapes were used. Small powder with mean size of 4 μm was used with two multi-component binder systems. Microstructures with dimension as small as 35 μm could be injection moulded. For successful moulding, the binder system must provide high green strength to withstand ejection from the mould and suitable moulding parameters used. For example, a high mould temperature is required and ejection speed must be reduced. The cross-sections of the microstructures are precisely replicated. The general shape in the depth direction is replicated although it is not as good as that for the cross-section. More work has to be conducted to realise the full potentials of the process.

Loh et.al. [13], study on the production of 316L stainless steel microstructures by μPIM. Silicon mould insert produced by deep reactive ion etching is used and the moulding conducted on a conventional injection moulding machine. Characterization of the powder and binder feedstock is conducted to enable the selection of suitable processing parameters. The study shows that microstructures of 100 μm diameter and height of about 200 μm can be produced by μPIM, but there are still problems to overcome.

With the great variety of processable materials, the PIM technique provides a good opportunity for the manufacturing of microsized or microstructured parts and components. MicroPIM has some requirements, which are not easy to meet concurrently. Feedstocks must have a high mechanical strength for deformation free demoulding. For good surface quality and complete mould filling of small and complex detailed microstructures, powders with small particle sizes have to be used. To reach a surface roughness of 1-2 microns, which is sometimes about one tenth of the smallest dimensions of the structures, submicron or even nanosized (50-100 nm) powders are necessary. On the other hand the solids content in the feedstocks should be as high as possible to reach a low and reproducible shrinkage with low tolerances. Merz et. al [14] investigates the feedstock development with advanced metallic and ceramic materials, such as 17-4PH stainless steel, hard metals (WC/Co), alumina, zirconium oxide, silicon nitride and a Al2O3/TiN composite.

In a more statistical technique, Ji et. al. [15] studies the final density of the 316L stainless steel moulded part after sintering using Taguchi method. This method is used in characterising and optimising the process factors for sintering water-atomised 316L stainless steel (average particle size of 6 μm). The sintering factors such as sintering temperature, heating rate, sintering time and sintering atmosphere were investigated and their report found that the chosen factors have significant effects on the final density. The optimal fractional final density of 96.14 % of wrought material was achieved with sintering temperature of 1250^{o}C, a heating rate of 20^{o}C/min and isothermal heating at 1250^{o}C for 90 min in a vacuum atmosphere. Whilst the sintering process carried on in the Argon and Nitrogen gas shows bigger pores structure.

Barriere et. al. [16] determines the optimal process parameters to produce parts by MIM without defects and with required mechanical properties. They used experiments and numerical modelling. The experiments are carried out with a multi-cavity mould specially designed and equipped to measure and record different parameters during the injection stage. The debinding and sintering cycles are also optimised in order to produce defect free components. The numerical modelling has been used using the biphasic flow formulation and a newly developed explicit algorithm; numerical simulations realised the segregation effects in injection.

According to Barriere et. al [16], the feedstock thermal conductivity is important for the injection duration because it characterises the heat dissipation rate in the injection process. The final parts is quite sensitive to segregation effects between powder and binder, thus rapid filling is necessary. During the debinding cycle, the temperature is controlled in an adapted manner to prevent the appearance of any crack. The debinding cycle may lasts from 5 to 36 hour, depending on its heating rates. Lower heating rate under approximately 300 ^{o}C produces better quality of the final product.

The sintering cycle is also important where it may influence the density of the final part. Ji et. al [15] writes further detail about the optimum parameter for the sintering. Barriere et. al [16], also agree with Ji et. al [15] that the most suitable atmosphere for sintering is in the vacuum atmosphere. During sintering, the part may shrinkage up to 20% of the original size, depending mainly on the percentage of metallic powder in the initial mixture. The mechanical properties of the sintered parts depend on many factors such as the chemical composition, microstructure, porosity and size of the debinded porous parts. In principle, the use of a very fine powder (diameter less than 20 μm) and well controlled high temperature (less than melting temperature) may lead to a nearly perfect densification. Reference [16] shows detail figures explaining the sintering cycle for 316L metallic powders.

4.5 CONCLUSION

Injection moulding, combining the advantages of powder metallurgy and casting of thermoplastic under pressure is a competitive production technology for powder articles. The main advantage of the method is production of quite accurate articles of complex shape for different purposes without the use of expensive complex presses and dies.

It is hoped that injection moulding technology is of interest not only to specialists and scientist in the field of powder metallurgy, but also a broader group of researchers and engineers in different branches of science and technology.

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