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CHAPTER 8

THE OPEN AIR ELECTRICAL-FIELD ACTIVATED SINTERING AND FORMING OF MICRO-COMPONENTS

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EXECUTIVE SUMMARY OF PROPOSAL

As the demand for the miniature products has increased significantly, so also has the need for these products to be produced in a rapid, flexible and cost-efficient manner. The application of electroplasticity shows significant potential to produce the components by using powder materials. Nevertheless, previous research has shown that there are still significant challenges to be met in order to achieve increased relative densification of product samples and simplification of the process. The process concept in this study comprises the combination of electrical-field activated sintering and forming processes. Therefore, the aims of the research were to establish the process concept for the manufacture of micro-components by using the machine that will be fabricated which could be used more practically in the small factories, whereas the Gleeble 3800 machine is more suitable for extended experimental work and further analysis in the laboratory. The cost to purchase the Gleeble 3800 machine was more expensive compared to the proposed fabricating machine. In addition to that, to design the iterations of die sets along with other tooling for machine setup to enable the series of experiment to produce of micro-components from powder materials. A comprehensive literature review on micromanufacturing, size effects, powder metallurgy and the electroplasticity process will be conducted. This efficient process has the potential to produce components with a high relative density around 90% or higher which was a difficult task to complete with the traditional method due to the influences from the size-effect issues in the micro-forming process and will contribute to the clean environment and decrease a pollution due to no usage of green compacts and argon gas. Changes in the particles concerning deformation and breaking are crucial in the course of achieving the densification in the proposed process which differs from a conventional sintering process.

DETAIL PROPOSAL

(a) Research Background

In general demands for micro-electromechanical systems (MEMS) and micro-products have significantly increased due to the fast growth that can be seen in the field of biomedicine, telecommunications and automotive engineering. For example, the global industry association Semiconductor Equipment and Materials International (SEMI) has released the sales forecast for semiconductor equipment which had a market value of $55.93 billion in 2017 to approximately $60.1 billion in 2018 and enjoys an active growth in the global market of 6.9% [1]. Besides typical MEMS manufacturing methods, significant efforts have been made recently either to scale down traditional processes or to develop the new ones for the manufacture of micro- and nano-products [2]–[5]. For instance, the production of micro-gears which are significant actuating and transmission components used widely in MEMS and micro-mechanical-systems (MMS), is often enabled through ultra-precision machining or lithographic techniques especially LIGA processes [6], [7]. Micro-forming also plays important roles for manufacturers of millions of micro screws through upsetting and rolling every year [8]–[10]. In addition to that, micro-extrusion has been well investigated where it is capable of extruding copper pins in the laboratory with a shaft diameter of 0.5 to 0.8 mm and a wall thickness of 50 to 125 μm [11], [12]. Therefore, based on the previous research and experiment results there is no doubt that micro-products with high precision and accuracy can be produced, nevertheless, concerning cycle time and cost for high production, there are still improvements to be made.

In micro-forming, the limits of the process are influenced largely by the workpiece's dimension. This phenomenon is being commonly referred as the size effects. The size effects that exist in metallic materials can be described as grain and feature/specimen size effects. According to Armstrong [13], grain size effect can be represented by the Hall-Petch law which states that the material strengthens as the grain size decreases. Meanwhile for feature/specimen size effects observed when the miniaturisation of the part occurs resulting in the decline of the flow stress. In this feature/specimen size effect, the workpiece cannot be considered as an isotropic continuum due to the huge share of the volume occupied by individual grains with different orientations if the microstructure, surface topology and tools of the workpiece used in the process remain unchanged [12], [14]. It was found that by decreasing the workpiece dimensions this could lead to an increase of friction factor by 20 times, when performing extrusion experiments on the CuZn15 brass alloy [14].

Moreover, micro-forming needs tools with overall sizes in a range of tens of microns. Electrical discharge machining (EDM) is often used as the main process of fabricating the micro-tooling. The advantage of the micro-wire EDM process is its capability to provide excellent results for producing a micro-tooling with a high accuracy of shape and good surface quality, but the process is lacking in geometrical flexibility [15]. Other technologies for micro-tooling such as die-sinking, drilling, grinding and milling were used for making tools for stamping, embossing and coining processes [16]. Overall, micro-tooling is expensive process to be made. The development of micro-forming technology renders challenges to micro-tooling. Besides the cost issue, tool life is one of the key factors that need to be considered. The fragile tool often needs to meet a high forming force requirement and tool wear at the micro-scale is often quicker than at the macro-scale due to the size effect issues and difficulties to fabricate the micro-components with intricate design. This was particularly the case when a high strength material was used in the micro-forming process.

Therefore, to overcome the problem that has been stated above, the development of new high-volume production and low-cost manufacturing capabilities are needed. The concept of this research comprises the combinations of electrical-field activated sintering and forming processes. It has a potential to address the existing problems and meet market needs especially for shortening the process chain, improving control of the shape of the part formed, reducing the forming pressure requirements, providing options to use different metal powders and combinations, improving the practicality of forming micro-components with high strength materials and reducing the influences of size effects. Among popular electroplasticity application, the spark plasma sintering (SPS) process has been claims for successfully formed components by many types of materials. Nevertheless, based on previous research, there are still significant challenges to meet the requirements of achieving high relative densification of samples and simplification of the processes [17]. In addition to that, Lange [18] stated that the densification process using the conventional powder sintering method involves a coarsening or neck growth, which is a critical mechanism needed to achieve densification caused by surface diffusion or evaporation/condensation. Thus, it is the reason why conventional powder sintering takes a long time to be completed. Meanwhile, by using the electrical-field activated sintering and forming process, the densification can be achieved more quickly, by deformation and breakage of the powder particles. It is not dependent on a spark discharge to create the heating as in the SPS process where it requires gaps for the spark to ignite, which as a result the application of pressure cannot be too high to prevent the spark from disappearing [19]. However, by using electrical-field activated sintering and forming process, the application of high pressurisation can be applied where it helps breakage and increase plastic deformation of material particles between interfaces. Based on this finding, it is essential for the particle breakage and deformation process to be present to achieve adequate and quick densification of micro-parts.

(b) Objective (s) of the Research

The aims of this research were to fabricate the electrical sintering machine, establish process configurations to produce micro-components with high densification from powder materials and design the die sets along with other tooling for machine setup, enabling a high-efficiency process. The concept of the process comprises combinations of electrical-field activated sintering and forming. The specific objectives of the research were:

1. To characterise a fundamental understanding of the densification mechanism of electrical-filed activated sintering and forming process.
2. To propose and fabricate the electrical sintering machine which could perform the direct electrical heating along forming force applied on the die set and sample inside it with temperature around 700 °C to 1300 °C and pressure about 75 MPa to 125 MPa.
3. To propose and fabricate the optimum die set and die set holder with an ejection mechanism for the sample produced by electrical-field activated sintering and forming process.
4. To identify the optimum process parameter by performing the

repetition of initial testing by using titanium, titanium alloy and copper powder to produce high relative density above 90% with short processing time.

(c) Expected Result / Benefit

1. Novel Theories/New Findings/Knowledge

Based on the research of the electrical-field activated sintering and forming process that will be conducted, the improvements will be shown concerning the shortening of the process time for the manufacture of micro-components with a variety of powder material. In the conventional powder sintering method, neck and grain growth is an important mechanism to achieve the densification of the sample. Thus, this is the reason why the conventional powder sintering takes a long time to become completed due to the grain growth which was caused by coarsening associated with the surface diffusion or evaporation/condensation at high-temperature. In addition to that, compared to the spark plasma sintering process, it was not depended on the spark discharge to create the heating but using the electrical-field current and assisted by the high pressurisation where the mechanical plastic deformation, breakage and interface melting of the particles make a significant contributor to the densification of the samples produced. It was essential for the particle changing process to be present to achieve satisfactory and quick densification of the micro-parts beside the Joule heat inducing the plasticity. There was also no plasma occurring in the powder system due to the low voltage applied and rapid contacts established by the high pressure which made it would not be possible to simulate electrodischarge during a rapidly compacted powder system. Meanwhile, for the spark plasma sintering process, it required gaps between the particles, to simulate the spark discharge which as a result the pressure that needs to be applied cannot be too high to prevent the sparks from disappearing. The main difference between electrical-field activated sintering and forming process with the spark plasma sintering process was the better efficiency of the current flow to heat the particles of the powder, the high heating rate during the experiment to speed up the process, pressure dependent on the densification of the samples along with the simplified process setup and control.

Hence, by taking consideration of the overview on the previous research compared to the research concept process which combines the micro-forming technology and the fast powder sintering with applying the external electrical-field currents alongside the high applied pressure simultaneously towards the die set and material particles of the samples, this offers some potential as shown below compared to the existing conventional processes.

- Fast sintering process;
- Short manufacturing cycles;
- No green compacts and argon gas needed;
- Easy to control the microstructure of the part formed;
- Options to use different metal powders and other materials combinations;
- Potential for forming structurally and functionally graded parts;
- Potential to form the bulk component with nano-structured materials;
- Feasibility of the forming for micro-components with high strength materials;
- Feasibility to form the 3D micro-parts with the dedicated micro-tool design and control;
- Reducing the influences from the size-effect issues in the micro-forming process.

2. Research Publications

Two (2) Indexed Journal with Impact Factor.

Total number of publications: 2

3. Specific of Potential Applications

The specific of potential applications are as below:

- The process can be used by the industry to manufacture micro-components or miniature due to the process involve fast sintering process and short manufacturing cycles.
- The process potential to form the bulk components with nano-structured materials.
- The process capable of reducing the influences from the size-effect issues in the micro-forming process.
- Feasibility to form the 3D micro-parts with the dedicated micro-tool design and control.
- Feasibility of the forming for micro-components with high strength materials.
- Potential for forming structurally and functionally graded parts.
- Options to use different metal powders and other materials combinations.
- Easy to control the microstructure of the part formed.

4. Number of PhD and Masters (by research) Students

In this research project there are no PhD and Master (by research) students.

(d) Methodology

1. Description of Methodology

A series of fundamental studies will be performed which consist of process concept evolution, a design of machine for the process, forming tools and process configurations for the experiments to achieve the aims and objectives as stated above. It started with a comprehensive literature review in the subject areas such as micro-manufacturing, size effects in micro-forming, powder metallurgy and the electroplasticity application in the sintering process. During the literature review, key manufacturing issues were identified, and solutions for technology advances proposed in detail.

These were followed by the fabrication of electrical sintering machine, process parameter configurations, die sets and other tooling for the use in a series of experiment by using several powder materials such as cooper, titanium, titanium alloy, etc. The purpose of the fabrication machine was to deliver the heating capabilities as Gleeble 3800 machine. The machine that will be developed could be used more practically in the small factories, whereas the Gleeble 3800 machine is more suitable for extended experimental work and further analysis in the laboratory. In addition to that, the cost to purchase the Gleeble 3800 machine was more expensive compared to the develop machine.

After the experiment were conducted, the effects of input parameters of experiments such as heating temperature, heating rate, holding time, pressure and use die set were discussed relative to the densification, microstructures and surface hardness of the formed samples. The comparison of higher sample densification with previous electroplasticity sintering process was made. Based on this discussion if the samples were not achieving excellent results, improvements of the experimental process

parameter and tool design were performed to increase high process efficiency and excellent product quality.
Finally, a general design and a manufacturing methodology by using electrical-field activated sintering and forming to produce miniature or micro-components from powder materials were establish.

2. Flow Chart of Research Activities

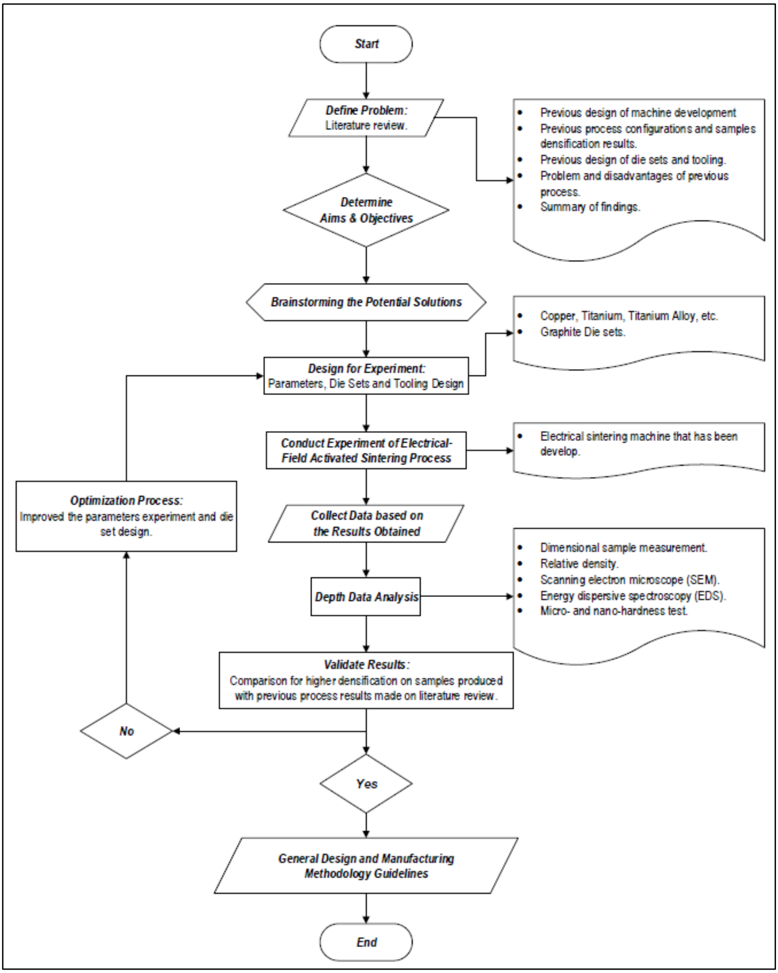

Figure 1: Flow chart of the research project.

3. Gantt Chart

No.	Description	Start Date	End Date

1	Process Fabrication of Electrical Sintering Machine	01-09-2018	31-12-2018
2	Process Design and Fabricate Die Set Holder and Ejection Mechanism	01-01-2019	30-04-2019
3	Process Concept of Electrical-Field Activated Sintering Forming	01-05-2019	31-08-2019
4	Die Set Design and Fabrication	01-09-2019	31-12-2019
5	Process Investigation with Electrical Sintering Machine and its Tooling	01-01-2020	31-05-2020
6	Report Writing and Finish	01-06-2020	31-08-2020

4. Milestone

No.	Description	Date
1	Preparation of the Machine and its Tooling	30-04-2019
2	Preparation of the Parameter for Experiments and Die Set	31-12-2019
3	Analysis of the Results Obtain from Experiment	31-05-2020
4	Report Writing and Submit the Report to Research Management Centre (RMC)	31-08-2020

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