GRAIN AND SIZE EFFECT: A REVIEW ON THEIR INFLUENCE IN MICRO-MANUFACTURING

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ABSTRACT

Size effects make most know-how of conventional machine is not suitable for the micro-manufacturing process. Material behaviour greatly varies in micro-sheet forming process with different sheet thickness. In this research, a tensile test and grain size test was conducted to determine their mechanical properties of the materials and their influence in micro-manufacturing process. Firstly, the specimens were prepared according to the ASTM-E8 standard. After the hot mounting samples of the tested materials were prepared, grain size of the material is observed through SEM. According to tensile experiment, stress-strain curve was plotted while the patterns of grain for each specimen were discussed. Based on both result, the influence of size effects for thin sheet metal and bulk material in micro-manufacturing process is discussed and compared.

ABSTRAK

Kesan saiz membuat kebanyakan kemampuan mesin konvensional tidak sesuai untuk proses mikro-pembuatan. Sifat bahan adalah berbeza dalam proses mikro-pembuatan dengan saiz ketebalan bahan yang berbeza. Dalam kajian ini, ujian tegangan dan ujian saiz butiran telah dijalankan untuk menentukan sifat-sifat mekanikal bahan dan mengkaji pengaruh sifat mekanikal bahan dalam proses mikro-pembuatan. Pertama, spesimen telah disediakan mengikut piawaian ASTM-E8. Setelah sampel bahan yang perlu diuji disediakan, saiz butiran bahan diperhatikan melalui SEM. Menurut eksperimen tegangan, lengkung tegasan-terikan telah diplotkan manakala corak bijirin bagi setiap spesimen telah dibincangkan. Berdasarkan kedua-dua keputusan eksperimen, pengaruh kesan saiz antara kepingan logam nipis dan kepingan logam tebal dalam proses mikro-pembuatan dibincangkan dan dibandingkan.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CNC	Computer Numerical Control
EDM	Electro-Discharge Machine
MEMS	Micro-Electromechanical System
SEM	Scanning Electron Microscope
UTM	Universal Testing Machine
UTS	Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.0 PROJECT BACKGROUND

Micro-lever, micro-connector, micro-screw and spring, are the example of the micro-parts which is widely used in mobile phones, IC industries, medical appliances, laptops, micro-navigation systems, and others. All these parts need high functionality, high reliance and accuracy. Therefore, micro-manufacturing are highly demand in various industries.

The demand from the global market for ever-smaller parts and systems at reasonable cost and superior performance is very strong. Micro-parts are widely used in a lot of the developing industries that have today in order to improve the quality of life and personal well-being including communications, electronic devices, healthcare so on.

Stamping is one of the popular and highly in-demand forming processes in producing metal parts. The metals-parts forming include wide variety of operations such as punching, embossing, coining, and blanking. The common examples of stamping process are video devices, aerosol spray cans, and automobile parts while the micro-stamping products are micro-devices and medical products.

The demands in micro-parts or products are totally high in recent years in order to improve the quality of life. Therefore, the key-issues in micro-manufacturing and micro-forming process especially in stamping processes are discussed in this paper.

Bulk forming process are exactly different with sheet forming process where the workability term is generally applied to bulk deformation processes such as forging, rolling, drawing and extrusion. In dissimilarity, the formability term is usually used in sheet forming process such as bending, deep drawing, stretch forming, and stamping, which the forces applied are primarily tensile.

A lot of researches have been studied and found that the material behavior in micro-scale is different from macro-scale. When the size of the material become smaller than 1mm, the size effect come-up, which is the methods of experimental and analytical are impossible to be used in micro-forming processes.

There are two different types of size effect which are feature size effect and grain size effect. The purpose of this project is to investigate the influence of the grain and size effect on material behavior in micro-manufacturing. Therefore, a tensile test has been carried out for both specimen; carbon steel sheet metal and stainless steel sheet metal as comparative studies on their mechanical properties such as strength, ductility, elastic modulus, and strain hardening. A grain size test is also conducted in this project research to observe the grain structure of the sheet metal.

The materials used are carbon steel sheet metal and stainless steel sheet metal with two different thicknesses of $50\mu m$ and $100\mu m$. The test first requires the preparation of a test specimen and prepared according to ASTM-E8M standards specifications which is the standard method testing for metal. Each specimen is subjected to uniaxial test. All the data are collected and the stress-strain curves are plotted.

1.1 PROBLEM STATEMENT

Although development on micro-machines experiencing lot of achievement, however there is less studies embarked on micro-scale material properties. Mechanical properties of thin sheet material are different from bulk material and size effect make most know-how on their mechanical properties is seen vital to guarantee successfulness of micro-forming process.

1.2 OBJECTIVES

The aims of the project are set as follows:

i) To identify key issues in micro-manufacturing
ii) To identify key issues in micro-forming process
iii) To study the influence of size effect on material behaviors for micro-forming application

1.3 SCOPE OF THE PROJECT

The specimens used are stainless steel and carbon steel with thickness 50μm and 100μm. This study involves laboratory work such as tensile test and grain size test. The preliminary work was to prepare the specimens for tensile test based on ASTM-E8M standards. Both specimens result are then compared.

CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

This chapter explains about research of the project that has been chosen and explanations about grain and size effect which influence in micro-manufacturing.

2.1 MICRO-MANUFACTURING IN GENERAL

In concerning to manufacturing systems, a miniature factory is understood to be a micro-factory that relatively to the new concept in terms of micro-manufacturing [Qin, 2006a; Okazaki et al., 2002; Okazaki et al., 2004]. Small manufacturing system that produce micro-parts in order to achieve the throughput target with less space and reduced the energy resources by decreasing the employees of production process can be defined as a micro-factory [Claessen et al., 2002]. All the necessary equipment needs to be reduced to the micro-scale which could reduce the energy consumption, maintenance cost, the preliminary and overhead cost, and also the material requirements. Hence, it's creating a more user-friendly production to the environment. The reduced mass of equipment will lead to increase the device speed and at the same time will increase the production rates by reducing the manufacturing cycle as the scale of equipment is reduced. As the advantage, the energy and the control loops for the equipment of small size are believed by many researchers to be much shorter [Qin,2006b].

Shrinking effects of production systems have been studied by a group of researchers from Mechanical Engineering Laboratory (MEL), Tsukuba Japan in 1990. Total energy consumption in factories reduced at about 1/100 compared to conventional plant in the estimated reduction case 1/10; the size of the production machine. The ability to produce parts with feature size less than 100µm [Byung et al.,2005; Chern et al., 2004; Chern et al., 2006b; Qin et al., 2008] or slightly larger than the thickness of human hair is the most significant advantage in micro-manufacturing. The slightest variations in the machine, vibration and any number of minute change, will have a direct impact on the ability to produce these kinds of features on the scale of production [Shanahan, 2006].

2.1.1 Micro-Products/Parts/Components

A greater part size than a few millimeters is regarded as a meso-part (as a reference, the meso-domain is defined as products fitting in a box of 200 x 200 x $200m^3$) [Kolesar et al., 2000]. The characteristic positional precision for such parts is expected to be in the range of 0.1 to 10µm. The application of method and techniques that cannot be applied in the meso-domain is allowed by the typical positional or the sometimes demands. The range of part and feauture-size machining capability is illustrates in Fig. 2.1. A maximum size of less than 5mm usually can be found in micro-electromechanical system (MEMS) application as known as miniature parts whereas the parts with machined features beyond 100µm.

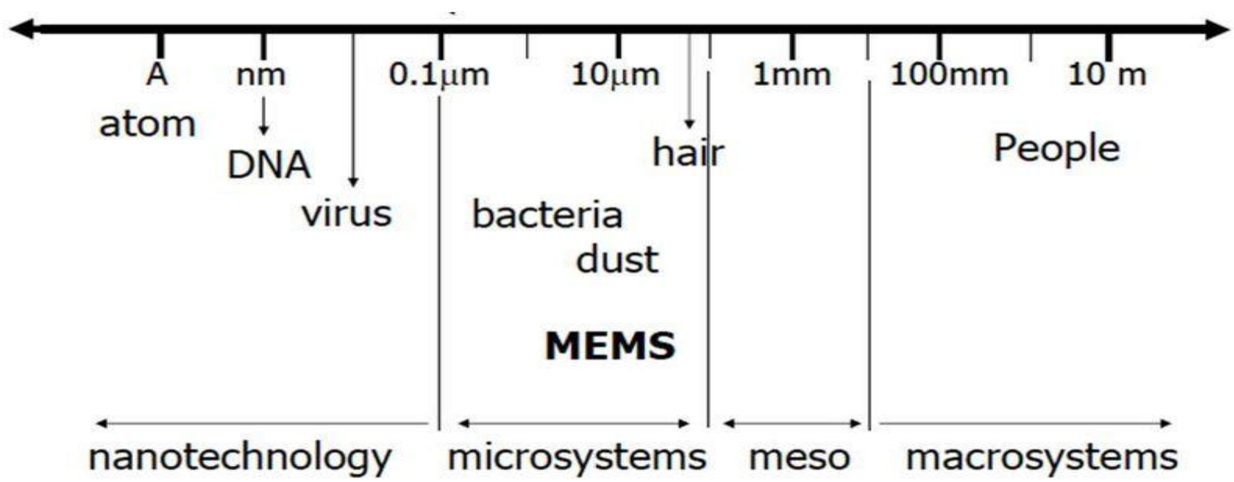

Fig. 2.1: MEMS scale of dimension

Source: Wikipedia, MEMS Magnetic Actuator

2.1.2 Micro-Manufacturing Methods and Processes

Producing the trend of micro-products in micro-manufacturing at the present time is more focused on miniaturizing or down-scaling both conventional and non-conventional methods. Nowadays, the combine two or more process together such as the hybrid manufacturing method is also the emerging methods [Chern et al., 2004]. Mechanical, chemical, electrochemical, electrical and laser process are the example categorized of manufacturing process according to the type of energy used in the process itself. The mechanical forces, thermal effects, ablation, dissolution, solidification, re-composition, polymerization or lamination, and sintering are the consideration of the working principles behind each process [Qin, 2009]. General manufacturing processes can also be classified into subtractive, additive, forming, joining and hybrid processes are the way in which components or products are to be made. The classification is equally appropriate to micro-manufacturing. Table 2.1 shows the typical manufacturing methods adjacent to the way of producing components or products.

Table 2.1: Typical methods/processes in micro-manufacturing (as presented by Qin, (2009)).

Process	Machine
Subtractive processes	Micro-Mechanical Cutting (milling, turning, grinding, polishing, etc.); Micro-EDM; Micro-ECM; Laser Beam Machining; Electro Beam Machining; Photo-chemical-machining; etc.
Additive processes	Surface coating (CVD, PVD); Direct writing (ink-jet, laser-guided); Micro-casting; Micro-injection moulding; Sintering; Photo-electro-forming; Chemical deposition; Polymer deposition; Stereolithography;etc
Deforming processes	Micro-forming (stamping, extrusion, forging, bending, deep drawing, incremental forming, superplastic forming, hydro-forming, etc.); Hot-embossing; Micro/Nano-imprinting; etc.
Joining processes	Micro-Mechanical-Assembly; Laser-welding; Resistance, Laser, Vacuum Soldering; Bonding; Gluing; etc.
Hybrid processes	Micro-Laser ECM; LIGA and LIGA combined with Laser-machining; Micro-EDM and Laser assembly; Shape Deposition and Laser machining; Efab; Laser-assisted-micro-forming; Micro assembly injection moulding; Combined micro-machining and casting; etc.

2.1.3 Micro-Manufacturing Machine/Tools

The vast and rapid development of micro-manufacturing technology gas covered almost all area in conventional machinery and processes as what has been experienced to date. Many researchers and companies have been proposed and developed the micro-machine in response to this continued development.

Research in micro-manufacturing focused more on assembly and conveyance processes, which research was led by the Japanese researchers and industries in the earlier age of micro-manufacturing development [Mishima et al.,2002; Ataka et al.,1999; Suda et al., 2000; Brussel et al.,2000]. This is lead to the bonding of similar development work by European countries, such as Project Miniprod developed by [Gaugel et al., 2001]. Effort was also widened up by the enlargement work of the mini-production system by Klocke Nanotechnik [Klocke et al., 2002; Klocke et al., 2003]. Nano-robotics module such as force sensors, water probers, manipulators, vacuum-grippers and micro-grippers are including in micro-factory. A gluing process, the transportation of parts and a multi-degree-of-freedom assembly process which was realized by various types of micro-manipulators are referred to as the development work.

Micro-manufacturing development was focused on the down-scaling of conventional milling and turning processes and once again was led by the Japanese researchers in the year of 2000 [Okazaki et al., 2004]. Equipment process of micro lathe with digital control system resolution was succeeded in the year 2000 by The Mechanical Engineering Laboratory, under the National Institute of Advanced Industrial Science and Technology, renowned as AIST. Fig. 2.2 below uses a pair of micro-sliders based on a unique step-feed configuration driven by PZT actuators, and a spindle unit mounted on the orthogonally-stacked micro-sliders in order to give it real machine-tool functionality. The displacement of each slider is detected using an embedded micro-linear-encoder with 62.5nm resolution developed by the Olympus Corporation and fed back to the servo-controller for numerical control. The part programs and feeds the servo-controller with command pulse trains yielding 0.1μm resolution processed by a single-board custom numerical-controller.

Fig. 2.2: Micro lathe with numerical control

Source: Okazaki et al., 2004

Good machining results has been produced by the machine which exceeds the standard of ISO 4287/1E [Davin et al., 2005]. Respectively, turning a brass rod, the surface roughness of the cylinder in the base-line direction and the roundness error were measured as 0.5µm *Rz* or 60nm *Ra*, and smaller than 0.5µm. Compare to those from regular-sized machines, these values are better than those of the original micro-lathe. Fig. 2.3 shows the NC motion-control enables programmed shape-generation.

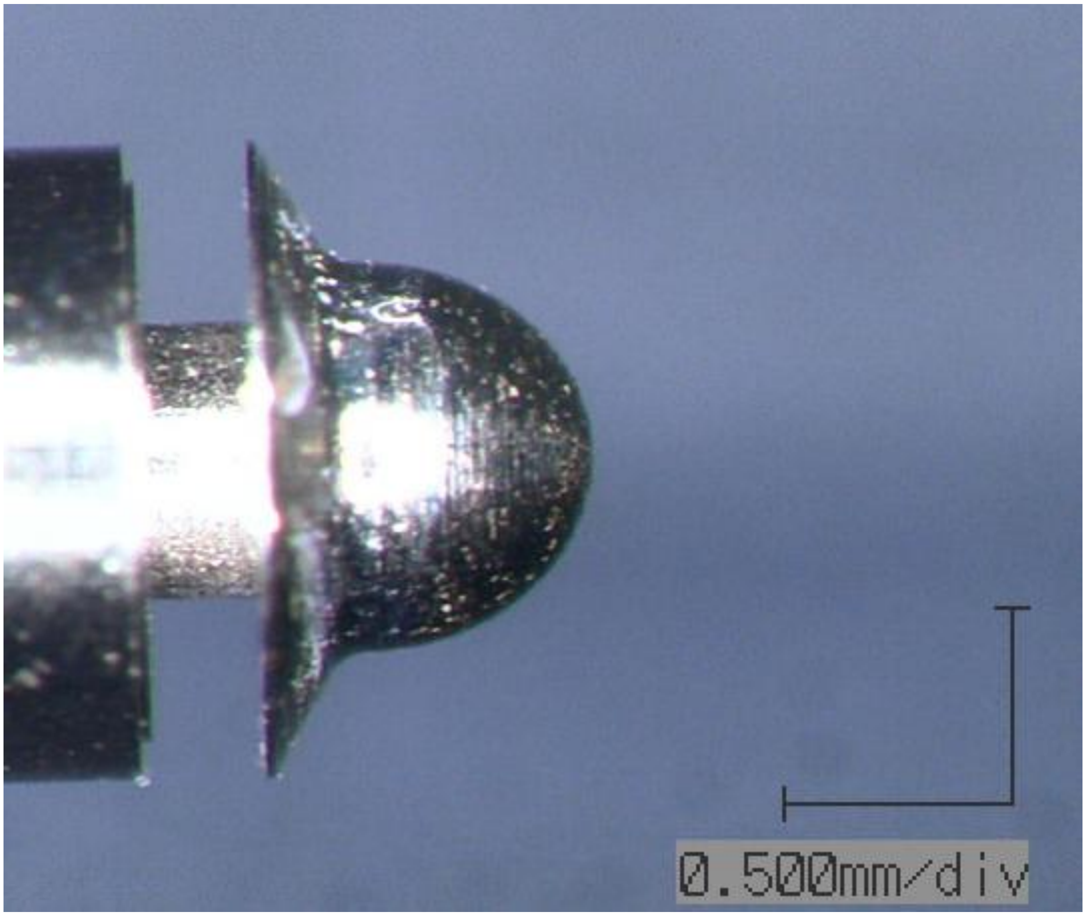

Fig. 2.3: Machined ‘microhat’ by MEL revised micro-lathe micro-machine

Source: Okazaki et al., 2004

The ‘Desktop Factory Study Group’ of the Nagano Techno Foundation consortium demonstrates another effort made on the development of micro-turning technology [Sankyoseiki].]. The group is collected of members from fourteen local companies and several institutions. The concept of the micro-factory in order to incorporate it into their manufacturing activities is developed by them. Performing of turning and milling operations, it has three linear axes and two spindles and equipped with an automatic tool changer. Machining tiny metal parts is able to evaluate the capability. Three months is required to the development process itself that was very intensive with the developing of an in-line desktop plating system, including pre/post-washing units. A de-burring machine, micro-drilling/turning/3D-milling/polishing machines, plating machines, washing machines, and assembling system have incorporated the concept into their dedicated products by the member of the companies.

The maturity of the miniaturization of conventional milling and turning process and its good potential was realized by one of the world's well-known servo and machinery-manufacturer, Fanuc in the middle of year 2000. Fig. 2.4 shows that Fanuc developed a machine with several combinations of high-precision multi-function machine functions called ROBOnano in year 2004, which can function as a five-axis mill, a lathe, a five-axis grinder, a five-axis shaping machine and high-speed shaper, this being realized by means of an air-turbine spindle instead of a conventional rotary servo-motor. The ROBOnano uses friction-free servo systems with all linear-slides and screws include static air-bearings. A high-speed shuttle unit capable of producing three grooves per second, and a 3 kHz fast tool servo using a lead zirconate titanate (PZT) actuator is use to done the shaping. A single-crystal diamond tool is nominally accomplished with cutting. A FANUC series 15i control is use with error mapping for positional axial errors to achieve control. The rotational axis is 0.00001 and the resolution of the linear axes is 1nm. Machine design is such does no backlash reactions and stick-slip motion.

Fig. 2.4: Fanuc ROBOnano versatile micro-machine

Source: Fanuc

2.1.4 Micro-manufacturing and Key Issues

Speak to production issues widely, the design of micro-products for micro-manufacturing needs to be able to succeed compared to the situation with prototype-products based on micro-technologies. The main goal for the design of micro-manufacturing should be the high-volume production of micro-components. Functional requirements need to be considered as well as micro-manufacturing-related factors renders more significant challenges, compared to those for the manufacture of macro-products when designing the product. Issues related to micro-manufacturing have been addressed intensively by many researchers [Qin, 2009; Alting et al., 2003]. Some typical issues to be addressed at the design stage of micro-manufacturing machinery are as follows:

i. **Factors negligible conventionally** – Conventional macro-scale machining has a limit to how conventional can be scaled down for miniaturization. Factors that can be ignored with conventional machining suddenly play a big part in micro-manufacturing beyond certain dimension such as vibration, tool-offset, temperature, the rigidity of the tools and the structure of the machines, and chip removal. These factors are more important because have a greater influence on micro-products.

ii. **Volume production and automation** – This is another issue that occurred in current micro-process technology is in terms of process automation. Every aspect on the process to need adjustments requires stand-alone and manual processes of the developed prototypes. The principal processes; pressing, milling, turning, and handling processes; material loading and unloading, tool positioning and aligning; are the most processes that were all manually configured and controlled by separate dedicated controllers to obtain precise and accurate motion and alignment. Micro-process suitable only for low yield-rate, and as-yet far removed from the potential of conventional processes which need this time-consuming process. According to this matter, manual adjustment tends to give greater parallax error compared to that with present automated closed-loop and programmable controllers that have error-compensation features [Fanuc; Kollmorgen; Baldor; Rockwell Automation; Yaskawa; Parker].

iii. **Limitation on machinable materials** – The only ductile and soft-materials with low-strength properties were chosen and studied as the test materials are mainly brass, copper and aluminum where in parallel with the fairly early stage of micro-machine development [Byung et al., 2005; Chern et al., 2004; Chern et al., 2006a; Okazaki et al., 2004]. Easily achievable due to such materials exhibiting low mechanical strength and tending to deform easily under low applied load or force is mean by the satisfactory machining of soft and ductile materials. Only simple micro-features were created effectively by the efforts made, which micro-features were far from being able to be used or useful. Some manufacturers have found that Soft materials are very restricted in their usage and these materials are not strong enough to meet the increasing demands of consistency and long life. The only option available is switching to harder and exotic materials.

iv. **Tooling dimension** – Tooling limitation is another key issue in micro-manufacturing development. 10μm end-mill tools that made from carbide (PMT) have been realized. 25-5-micron milling and drilling tools presently have been found suitable and can be found commercially [Kyocera; Minitools]. There is still limitations existing which limits the applicability of the tooling, although micro-tooling development started more than a decade ago [Aronson, 2003; Aronson, 2004]. The aspect ratio defined as the ration of the tool diameter to the drilling depth of 5 to 10 have been found suitable, and some have aspect ratios of even lower than five. Tooling breakage result from the deeper-plunging-and drilling process and make the tooling is unsuitable for the aerospace- and automotive-industries, which require very-high-strength material of low mass. The achievable accuracy of the drilled holes has not yet been studied extensively. Moreover, issue regarding the aligning of micro tools of sub-micron precision has not yet been explored widely because no automatic machine is available at present capable of aligning tools of sub-micron precision [Kibe et al., 2007].

v. **Unwanted external forces** – The main problem encountered in the handling of micro-parts is precise positioning [Rougeot et al., 2005]. The external forces concerned in physical contact, such as the electrostatic, sticking or adhesion effect, and Van Der Waals force, have become key issues and several studies have been made to understand the situation and the strategy required to eliminate those forces, employing mathematical simulation [Arai et al., 1995; Arai et al., 1997; Feddema et al., 1999; Rollot et al., 2000; Fearing et al., 1985; Bowling et al., 1986; Bowling et al., 1988; Tomas et al., 2007].