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A Review on Micro-manufacturing, Micro-forming and their Key Issues

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Abstract

Micro-manufacturing has received good attention globally in terms of its manufacturing methods/processes. One of the most popular micro-manufacturing processes is micro-forming. Many efforts have been focused on micro-forming, mainly on the micro-stamping process due to the process itself contributing numerous products, especially in its conventional macro-process. Most every-day products are made by this process. Although there were efforts made to realize micro-forming for industrial application, the technology itself was seen as being insufficiently mature. Much development work needed to be done, specifically to develop a fully-automated high-volume production micro-forming machine, which is reliable and at all times ready for operation in terms of its processes, tooling, and material-handling to ensure the successful production of micro-products. The paper addresses key issues encountered by researchers worldwide on both micro-manufacturing, specifically micro-forming.

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1. Micro-manufacturing in General

The term ‘micro-manufacturing concept’ in the context of a miniature factory is understood to be a micro-factory and it is a relatively new concept concerning manufacturing systems [1-4]. A micro-factory can be defined as a small manufacturing system conceived as a means of achieving higher throughput with less space and reduced consumption of both resources and energy via downsizing of production processes [5]. This means that all of the equipment has necessarily to be reduced to the micro-scale (micro-machines) which could, in-turn, reduce the energy consumptions, preliminary and overhead costs, and material requirements, along with reducing pollutions and creating a more user-friendly production environment. As the scale of the equipment is reduced, the mass of the equipment itself can be reduced dramatically and this will lead to the increasing of tool speed and at the same time will result in improvement of the production rates by the reduction of the manufacturing cycle. In addition to the foregoing advantageous, the force/energy loop and the control loops for small-size equipment are believed by many researchers to be significantly shorter.

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In 1990, a research group from the Mechanical Engineering Laboratory (MEL), Tsukuba Japan, studied the effect of miniaturization of production systems. The estimation was made that in the case of a 1/10 size reduction of production machines, the total energy consumption in the factory decreases to approximately 1/100 compared to that of the conventional factory. The most significant advantage of micro-manufacturing is the capability for producing parts which having feature sizes of less than 100 μm [6-9], or little greater than the thickness of a human hair.

At this scale, the slightest variation in the manufacturing process caused by material or cutting tool characteristics, thermal variations in the machine, vibration and any number of minute changes, will have a direct impact on the ability to produce features of this type on a production scale.

2. Micro parts definitions

A meso-part is regarded as a part that is greater in size than a few millimeters (as a reference, the meso-domain is defined as products fitting in a box of 200 x 200 x 200mm³) [10]. However, a micro-part is concerned with small parts with typical part-dimensions in the range of sub-millimeters up to a few millimeters, although part-features may be in the micro-meter range. The typical positional precision for such parts is expected to be in the range of 0.1 to 10 μm . The micro-domain allows for, and sometimes demands, the application of methods and techniques that cannot be applied in the meso-domain

3. Micro manufacturing methods and processes

The trend for micro-manufacturing at the present time is more focused on miniaturizing or down-scaling both conventional and non-conventional methods to produce micro-products. Additionally, there are also emerging methods, such as the hybrid manufacturing methods, which combine two or more processes together [8]. Manufacturing processes can be categorized according to the type of energy used in the process itself, such as mechanical, chemical, electrochemical, electrical and laser processes. The working principles behind each process include consideration of mechanical forces, thermal effects, ablation, dissolution, solidification, re-composition, polymerisation/lamination, and sintering [11]. According to the way in which components/products are to be made, general manufacturing processes can also be classified into subtractive, additive, forming, joining and hybrid processes. The classification is equally applicable to micro-manufacturing. Typical manufacturing methods against the way of producing components/products are show in Table 1.

Table 1: Typical methods/processes in micro-manufacturing [11].

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.

4. Micro-Manufacturing Machines/Tools Micro

As to what has been experienced to date, the vast and rapid development of micro-manufacturing technology has covered almost all area in conventional machinery and processes. In response to this continued development, many researchers and companies have proposed and developed their micro-machine prototype. In the earlier age of micro-manufacturing development, research in micro-manufacturing focused more on assembly and conveyance processes, which research was led by the Japanese researchers and industries [12-15]. This in turn led to the booming of similar development work by European countries, such as Project Miniproduct developed by [16]. Effort was also widened up by the development work of the mini-production system by Klocke Nanotechnik [17-18]. The micro-factory includes a nano-robotics module with a repeatability of 50nm. Later, in the year 2000, micro-manufacturing development was focused on the down-scaling of conventional milling and turning processes and once again was led by the Japanese researchers [4]. For instance, The Mechanical Engineering Laboratory, under the National Institute of Advanced Industrial Science and Technology, renowned as AIST, succeeded in the year 2000 in equipping a micro-lathe with a precision digital-control system. Another effort made on the development of micro-turning technology was demonstrated by The 'Desktop Factory Study Group' of the Nagano Techno Foundation consortium [19]. The group is composed of members from fourteen local companies and several institutions. They are developing the concept of the micro-factory in order to incorporate it into their manufacturing activities. In 2003 they developed a unique desktop-sized turning centre of which the machine is only about the size of an A3 sheet of paper. In the middle of year 2000, 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 year 2004 Fanuc developed a machine with several combinations of high-precision multi-function machine functions called ROBOnano, which can function as a five-axis mill, a lathe, a five-axis grinder, a five-axis shaping machine and a high-speed shaper, this being realized by means of an air-turbine spindle instead of a conventional rotary servo-motor. In the year 2006, a group of researchers from the University of Strathclyde developed a micro-forming machine [6, 20]. The machine is driven by a direct drive precision linear motor and has a capability of mass producing 16 parts in every second. The micro-forming machine operation was fully autonomous where the high precision feeding and parts transport systems were fully integrated with the machine.

5. Micro-manufacturing and Key Issues

The design of micro-products for micro-manufacturing needs to address production issues extensively to be able to succeed compared to the situation with prototype-products based on micro-technologies. The high-volume production of micro-components should be the main goal for the design of micro-manufacturing. When these products are designed, not only will functional requirements need to be considered, but also micro-manufacturing-related factors will have to be taken into account. This is because manufacturing these products renders more significant challenges, compared to those for the manufacture of macro-products. Issues related to micro-manufacturing have been addressed intensively by many researchers [11, 21]. The followings are some typical issues to be addressed at the design stage of micro-manufacturing machinery.

5.1. Factors negligible conventionally

There is a limit to how far conventional macro-scale machining can be scaled down for miniaturization. Beyond certain dimensions, factors that can be ignored with conventional machining suddenly play a big part in micro-manufacturing: vibration, tool-offset, temperature, the rigidity of the tools and the structure of the machines, and chip removal, are more important because these factors have a greater influence on micro-products.

5.2. Volume production and automation

Another issue occurred in current micro-process technology is in terms of process automation. Stand-alone and manual processes of the developed prototypes have required every aspect on the process to need manual adjustments. Most of the processes such as principal processes; pressing, milling, turning etc, and handling processes; material loading and unloading, tool positioning and aligning; were all manually configured and controlled by separate dedicated controllers to obtain precise and accurate motion and alignment. This time-consuming process has made micro-process suitable only for low yield-rate, and as-yet far removed from the potential of conventional processes. On top of 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.

5.3. Limitation on machinable materials Structure

In parallel with the fairly early stage of micro-machine development, only ductile- and soft-materials with low-strength properties were chosen and studied as the test materials; mainly brass, copper and aluminum [4, 7-9]. The satisfactory machining of soft and ductile materials is easily achievable due to such materials exhibiting low mechanical strength and tending to deform easily under low applied load/force. Only simple micro-features were created successfully by the efforts made, which micro-features were far from being able to be used or applied. Soft materials are very limited in their usage and some manufacturers have found that these materials are not durable enough to meet the increasing demands of reliability and long life. Therefore, switching to harder and exotic materials is the only option available.

5.4. Tooling dimension Structure

Another key-issue in micro-manufacturing development is tooling limitation. At present, 10 μ m end-mill tools have been realized, these tools being made from carbide (PMT). 25-50micron milling- and-drilling tools currently have been found satisfactory and can be found commercially [22-23]. Although micro-tooling development started more than a decade ago, there is still limitations existing, which limits the applicability of the tooling [24-25]. Only aspect ratios (the ratio 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. Deeper-plunging and-drilling will result in tooling breakage, hence, makes the tooling unsuitable for the aerospace- and automotive-industries; which require very-high-strength material of low mass. The achievable precision of the drilled holes has not yet been studied extensively and, furthermore, issue regarding the aligning of micro tools of sub-micron precision has not yet been explored extensively because no automatic machine is available at present capable of aligning tools of sub-micron precision [26].

5.5. Unwanted external forces Structure

Precise positioning is also a main problem encountered in the handling of micro-parts [27]. The external forces involved in physical contact, such as the electrostatic, sticking or adhesion effect, and Van Der Waals force, have become key issues and numerous studies have been made to understand the situation and the strategy necessary to eliminate those forces mathematically and practically [29-35].

5.6. Sensor dimension and performance Structure

Moreover, attention has to be paid to sensor's accuracy, since the sensors available at the present time are bulky in size and the achievable precision is basically of the order of tenths of microns. Being excessive large in size makes the sensors difficult to be placed accurately on a tiny workspace, while this level of precision is not feasible for micro-parts application, which requires at least sub-micron precision. In addition, most of the calibration-precision capability of current machines is far less than the precision demanded on micro-handling.

6. Sheet-Metal Forming and Stamping Structure

Sheet-metal components are used extensively in various applications such as vehicles, aircraft, electronic products, medical implants and packaging for consuming goods, typical parts/components including car-panels, aircraft skins, cans for food and drinks, frames for TV/computer screens/monitors/displays, etc. Concerning miniature/micro-products, sheet-metal parts include electrical connectors and lead-frames, micro-meshes for masks and optical devices, micro-springs for micro-switches, micro-cups for electron guns and micro-packaging, micro-laminates for micro-motor and fluidic devices, micro-gears for micro-mechanical devices, casings/housings for micro-device assembly/package, micro-knives for surgery, etc. Therefore, sheet-metal parts are closely associated with everyday life.

Basic process-configurations for the forming of macro-products include shearing, blanking, bending, stamping, deep drawing (including mechanical and hydro-mechanical), hydro-forming, stretching forming, super-plastic forming, age forming, spinning, explosive forming, incremental forming, etc.

One of the popular and highly-in-demand forming processes is stamping. Metal stamping has been defined as a process employed in the manufacturing of metal parts with a specific design from sheet-metal stock and includes a wide variety of operations such as punching, blanking, embossing, bending, flanging and coining [36]. Common examples are sheet-metal machines, automobile parts, metal components used in audio- and video-devices, aerosol spray cans, and even military tanks. A household example is the use of sheet metals to make pots and pans.

Sheet metal can be deformed into different pre-determined shapes. The metal must be malleable and needs to flow easily in order to be drawn into various shapes. Stamping can be done on metals such as aluminium, zinc, steel, nickel, inconel, titanium, bronze, copper and other alloys. The process itself is a mass-production, which is very economical process with low cycle time. Hence, it is widely used in the manufacturing of large-volume products with semi-skilled labour. The process is also called chipless manufacturing.

Metal-stamping process uses dies and punches to cut the metal into the required shape. The male components are called punches and the female components are called dies. Press machine-tools are used in the stamping process. The die, made of hardened steel, has a contour that matches the shape of the finished part and is mounted on the table of the press. The punch, made of hardened tool-steel or carbide, also matches the contour of the part but is slightly smaller to allow clearance between the die and the punch. It is mounted in the head or the turret, which moves down and punches the metal. The thickness of the sheet metal does not change during this process.

7. Micro-Stamping Processes

Numerous research investigations have been conducted worldwide covering the micro-forming field and showing that micro-forming is on a promising path towards its application in industrial production [37-43]. Moreover, metal forming offers some attractive characteristics that are superior to those of other processes, for example, machining and chemical etching, considering such features as high production-rates, better material integrity, less waste, lower manufacturing costs, etc. Therefore, micro-forming could be a better option for the mass-manufacture of micro-products at a reduced cost, provided that a proper manufacturing facility is developed.

Literally the same as in the conventional stamping process but, instead, macro- and meso-scale products being produced, micro-stamping is intended to produce miniaturized products and components. Micro-stamping is seen useful to produce parts such as wristwatch and micro handheld-device components, medical products etc. [36].

The early stages of micro-stamping development showed a gradual development of the process. Effort had been expended to perform an automatic and hybrid simple punching process on brass strip [8, 44]. This effort continued with the development of a manually-operated micro-stamping machine with the capability of employing various punch shapes [7]. The latest efforts in micro-stamping development have demonstrated that multi-stage/progressive die micro-stamping may be used for the micro-sheet-forming process [6]. A fully-automatic linear-motor-driven multi-stage/progressive-tool micro-stamping machine has been developed with collaboration between the University of Strathclyde and its European Union partnership. In the micro-stamping process, not only is the machine itself physically scaled down, but the tools required for the process also have to be capable of producing the required micro-parts through scaling down. Efforts made by [6] have demonstrated the successful operation of single-stage and multi-stage tooling for the micro-sheet-forming process. Various parts with micro-features have been produced successfully.

8. Micro-Stamping Machines and Tools

The research trend began with fundamental studies of every aspect in micro-forming, covering the work material and the appropriate tooling [37, 43, 45]. Later, in mid-2000, the effort was extended to the development of a micro-forming-machine prototype by groups of researchers as well as joint-venture industries [6, 38, 46-47].

The initial development of the micro-forming-machine prototype was traditionally based on conventional forming machineries and focused on a diverse range of forming processes, which included stamping and bulk-forming processes. Effort made by [7] and [8] validated the punching of thin sheet-metal by micro-punch. In [8] the punching process was actuated by a high-force DC solenoid and material feeding was done by an automatic roll-feeder. The results demonstrated a successful punching process, different punch geometries being used. [7] demonstrated an entirely manually-controlled punching process with a micro-punch.

A new, low-cost, bench-top machine dedicated for micro-sheet-forming was developed at the University of Strathclyde [6], with collaboration with EU MAMSICRO consortium partners. A linear-motor driving mechanism was used. The maximum frequency of the machine is 960 strokes per minute (spm), the maximum force is 5.3kN, the vertical-position resolution is 0.1 μ m, and the load-measurement resolution is 0.1N. The machine enables the micro-stamping/forming of sheet-metal parts (ideally for sheet metals of a thickness of less than 100 μ m). The machine has a maximum working space of 400mm x 400mm with a flexible set-up, due to having a modular design, in which the ram-driven form/power is changeable without need of changing other machine set-ups; and four machine-frame columns and supports to the ram guiding bridge can be re-positioned according to the requirements, as well as the sheet-metal feeder, and the part carrier. The bridge for guiding the ram is separated from the main machine frame, and hence it is not affected significantly by the deflection of the main frame and by vibration. Other innovations include monitoring the displacement directly on the tooling

(therefore being able to control the punch stroke more accurately), transporting the miniature/micro-parts directly out of the dies by a part transport system, a new vacuum/compression-air chamber design, a new sheet-metal holding design, etc. The machine design was supported by finite-element dynamics analysis, which led to the development of a bench-top machine that has very good dynamic performance and machine stability (no connection to the bench is needed, and no significant vibration is felt on the shop-floor). A similar machinery-concept was developed before by [46] to serve bulk-forming process. A linear motor was used to drive the forming tool: the concept was proven to be successful.

9. Key Issues Related to Micro-Stamping Quality

Among various micro-metal components, sheet-metal components are used very extensively in MEMS, micro-electronics/optical devices, medical devices/instruments, etc. There has been significant interest in the research into micro-sheet-forming [3, 6, 9, 12, 43, 46, 48-56]. Nevertheless, most of this research did not address production issues sufficiently, in terms of considering the transfer of the laboratory processes/machines to volume production. One of the key issues relates to the automation of the stamping processes by continuously feeding thin sheet-metals with micron-range precision.

9.1. High-precision handling and product quality

Feeding sheet-metals in conventional press-working is no longer a major problem in production [57]. However, challenges arise when thinner metal-strips are to be used in micro-sheet-forming (e.g. $<100\ \mu\text{m}$) and the parts/features to be formed become smaller (e.g. sub-millimeter ranges). In these cases, the forming a micro-sheet-metal component may require the feeding/positioning of the sheet-metal under the forming tools to be as accurate as within one to a few microns. This is particularly important in multi-stage progressive micro-stamping, in which the neighboring features of a part may be very close to each other. Therefore, the feeding of the sheet-metal has to be very accurate in order to prevent any inaccurate forming or damage to the neighboring features and connections of the part/scrap to the strip.

9.2. High-precision handling to meet volume production

For volume production, feeding the strip (sheet metal) accurately may have to be achieved with a reasonable feed rate, e.g. 120 strokes per minute, for which the stiffness of the thin strip may be a major concern.

Precision feeding for micro-sheet-forming as described above cannot be achieved with conventional, large-scale sheet-metal feeders. Feeding in micro-sheet-forming was addressed only occasionally [9, 46] in some studies. Detailed study on the feeding mechanism and performance of the feeders (positional precision) in micro-sheet-forming, considering various process conditions and material parameters has not been undertaken previously.

9.3. Material's mechanical properties

Usually negligible factors in macro-size materials such as material size effects may not be neglected in micro-parts/size productions. Studies had shown that material behavior varies greatly with the decreasing of the scale [58-60]. When feature size of a part is reduced to less than 1mm, the so-called size-effect arises, which means that knowledge in terms of empirical and analytical know-how of the conventional process cannot be applied directly in the micro-scale production world. Research efforts elsewhere had been made and the results of which had confirmed that material behavior at micro-scale was different from that at macro-scale specifically when micro-forming processes are involved [40, 61]. Therefore in every micro-forming related process, specifically in micro-sheet-forming, studies and analyses of each material used for the process have to be considered as indispensable in order to be able to understand their behavior and to be able to correlate their behavior with the micro-forming processes.

10. Conclusions

Micro-manufacturing has received good attention globally in terms of its manufacturing methods/processes. One of the most popular micro-manufacturing processes is micro-forming [6-9, 59, 62-63]. Many efforts have been focused on micro-forming, mainly on the micro-stamping process due to the process itself contributes to numerous products, especially in its conventional process. Most every-day products are made by this process. Although there were efforts made to realize micro-stamping for industrial application, the technology itself was seen as being insufficiently mature. Much development work needed to be done, specifically to develop a fully-automated high-volume production micro-stamping machine, which is reliable and at all times ready for operation in terms of its processes, tooling, and material-handling to ensure the successful

production of micro-products.

Although effort on the development of a micro-stamping machine has been successful vindicated for high-yield production and has confirmed some of the preliminary concepts, there is still lack of effort to address material handling for the micro-stamping process. Feeding sheet-metals in conventional stamping is no longer a major problem in production. However, challenges arise when thinner metal-strips are to be used in micro-stamping (e.g. <100 μm) and the parts/features to be formed become smaller (e.g. sub-millimeter ranges). In these cases, the stamping of a micro-sheet-metal component may require the feeding/positioning of the sheet-metal under the forming tools to be as accurate as within one to a few microns. This is particularly important in multi-stage progressive micro-stamping, in which neighboring features of a part may be very close to each other. Therefore, feeding the sheet-metal has to be very accurate in order to prevent any inaccurate forming or damage to the neighboring features and connections of the part/scrap to the strip.

In addition to this, another challenge is to meet high-volume production capability. High-precision material handling is somewhat difficult to achieve in conjunction with high-speed motion. Negligible factors such as the machine's stiffness and rigidity, vibration and changes of temperature in the conventional-stamping process can no longer be neglected in micro-stamping material-handling. Therefore, an effort has to be made to realize high-precision material-handling for micro-stamping application by addressing the solution of the two key issues.

Negligible factors in conventional process such as material's size effect may not be neglected in micro-forming. Although this issue has been acknowledged by researchers worldwide, still more efforts have to be embarked to establish material mechanical properties' database with materials' size effect is taken into account.

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