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A structured approach to integrate MEMS and Precision Engineering methods☆

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ABSTRACT

Two different kinds of manufacturing technologies are used to produce micro systems or micro structures on macro-scale parts. MEMS (micro-electro-mechanical systems) are produced by using bottom up techniques such as lithography, etching and bonding, which were adopted from well established microelectronic manufacturing processes. Precision Engineering systems apply a top-down approach and use very precise versions of conventional manufacturing techniques such as milling, turning or powder injection molding to produce micro-mechanical parts. At the present time, both technologies face the challenge of long iterative product development cycles before the functionality of the product and the set-up of the production system can be verified. A structured, systematic, and rational design approach including the verification of both the product's functionality and its efficient manufacturability is necessary to enable the fast development and cost-effective production of so-called killer applications. Even though both approaches offer complementary advantages concerning the range of materials, design flexibility and the capability to produce parts in small and large volumes, there have been no attempts to integrate the two technologies up to now. Through the framework of axiomatic design, this paper proposes a structured approach to derive and simultaneously verify micro systems and the necessary manufacturing processes by applying and integrating both Precision Engineering and MEMS techniques.

1. Introduction

Micromanufacturing has become one of the key technologies of the 21st century and it is expected to grow annually at a rate of 20% [1,2]. Two different kinds of manufacturing approaches have been used to economically miniaturize components.

The first approach is based on a set of manufacturing methods developed for the integrated circuit industry. These techniques are generally monolithic and are capable of fabricating 2–2 dimensional parts in a specific set of materials. In this paper we refer to parts and systems that are manufactured by monolithic micro technology as MEMS (micro-electro-mechanical systems) and the respective production processes as MEMS processes.

The second technology for producing miniaturized components and devices is Precision Engineering and uses extreme versions of conventional manufacturing techniques like micromilling, microturning, microdrilling etc. Precision Engineering processes are characterized by their flexibility (short processing time for small and medium sized batches) and their ability to produce complex 3-dimensional geometries in a broad mix of materials. The machining of complex features in wear resistant materials like metals or ceramics makes Precision Engineering suitable for micromanufacturing.

This paper deals with the problem in both micromanufacturing approaches of the long iterative product development cycles which are required to verify the functionality of the product and to set-up of the production system. By providing a detailed overview of the challenges and limitations for the design of micro-scale products and their respective production processes this paper offers an explanation for why there are few killer applications in micro technology. The integration of the two micro technology approaches via axiomatic design is presented with two case studies on the design of a diesel fuel injector and a digital on-demand deposition process.

2. Challenges in the design of micro systems

Even if the annual forecasted growth rates of MEMS and micro systems made by Precision Engineering look promising, up to now there have been few killer applications aside from acceleration sensors for airbags and ink jet printer heads.

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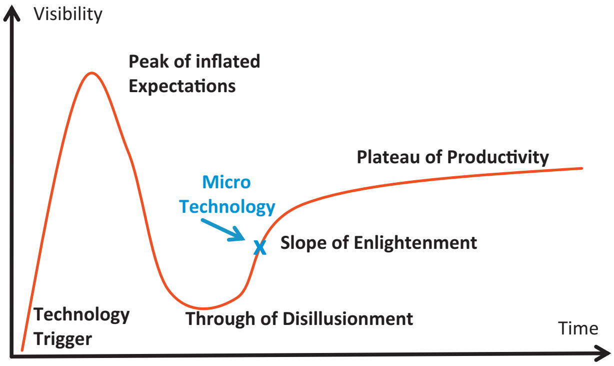

Fig. 1. Gartner Hype Cycle with respect to micro technology.

Certainly this is related to the fact that micro technology is still an emerging discipline. According to the Gartner Hype Cycle [3] the public perception of an emerging technology can be divided into five distinct phases (Fig. 1).

The first phase of a Hype Cycle is the "technology trigger" or breakthrough that generates significant press and interest. For micro technology this occurred in the late 1980s when the first applications in the automotive and consumer market appeared. The "Peak of Inflated Expectations" – a frenzy of publicity typically generating over-enthusiasm and unrealistic expectations – was reached in the late 1990s when for example micro submarines travelling through blood-vessels [4] and cyborg insects for locating earthquake victims [5] were envisioned.

New technologies enter the "Trough of Disillusionment" because they fail to meet expectations and quickly become unfashionable. The authors are of the opinion that micro technology is currently located on the "Slope of Enlightenment." The advantages of miniaturization are accepted and most of the physical laws of the micro world have been studied. However, the "Plateau of Productivity" will not be reached within the next 5–10 years unless we overcome the two major challenges in making this technology productive and broadly applicable in the near future.

2.1. Strict separation of Precision Engineering and MEMS approach

Within the last two decades two separated technologies for the production of micro systems have emerged (Fig. 2). The first technology which the authors refer to as MEMS processes uses bottom up techniques such as lithography, etching and bonding, which were adopted from well established microelectronic manufacturing processes. The second technology which the authors refer to as Precision Engineering applies the top-down approach using specialized versions of conventional macro scale manufacturing techniques such as milling, turning or powder injection molding to produce mainly micro-mechanical parts.

MEMS are mainly 2- or 2-dimensional and consist of materials ranging from silicon (silicon dioxide, silicon nitride), glass and quartz to aluminum, tungsten and gallium arsenide. Up to now small volume production is in the early stages (i.e. direct printing) [6,7] whereas large batch production is well established due to standardized mass production processes adopted from the microelectronic world such as photolithography, bulk and surface micro machining.

Micro systems made by Precision Engineering offer the advantage of 3-dimensional geometries with possible freeform surfaces. Furthermore, there is almost no limit for material usage in terms of hardness and electrical conductivity (polymers, metals and ceramics) which allows the usage of low-wear and temperature-resistant substances. In contrast to MEMS processes, in Precision Engineering the production of components in rather small quantities by EDM, micro milling or laser ablation is well established. However, the production in large volume with micro powder injection molding or micro forming is in its early stages.

Despite the apparent complementary advantages of both technologies in terms of freedom of geometry, production rate, standardized processes and material range, there has been little attempt to integrate the two technologies. As the design of MEMS is mainly driven by the question of how functionality can be fulfilled using established microelectronic processes, the design and functionality of micro systems made by Precision Engineering is mostly guaranteed by standardized geometric features such as bearings, gear wheel. Therefore, design approaches of both technologies differ in many aspects (Table 1).

In the bottom-up approach, MEMS functionality is achieved by using well-established semiconductor processes. Silicon, for example, is often used even if its electrical properties are not required because the tools and instruments needed for micro fabrication are designed to match the characteristics of silicon wafers [8]. Thus, the current MEMS design approach may sometimes be driven by the question of how functionality can be achieved using established microelectronic processes such as

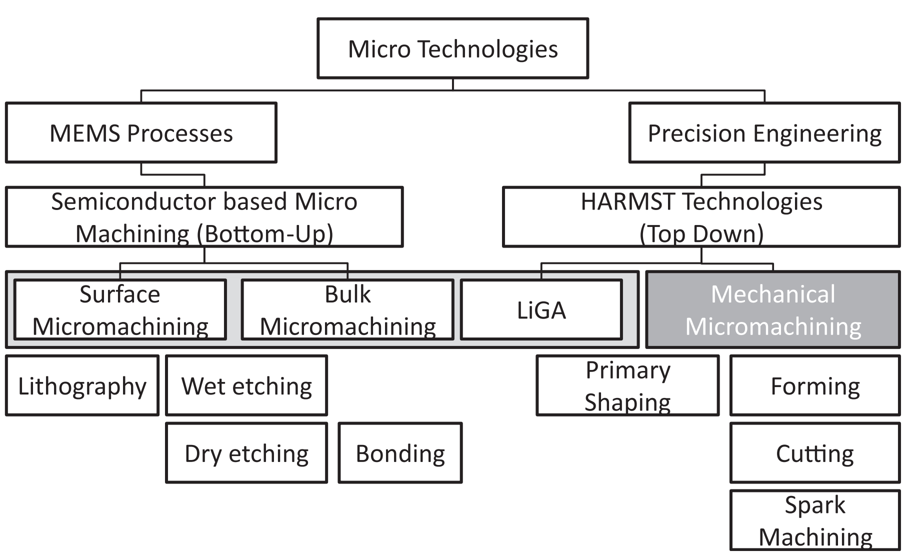

Fig. 2. Structuring of micro manufacturing techniques.