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The evolution of molds in manufacturing: from rigid to flexible

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Abstract

Nowadays, dynamic products life cycles and increase in the number of product variants have led to reduction in demand per variant. This modern trend is in contrast with the high production volume of manufacturing processes such as injection molding, since they are commonly employed for mass production due to their long changeover time. Traditional rigid molds do not seem to be able to cope with the current industrial and market challenges. Flexible and reconfigurable molding processes, such as the discrete pin tooling systems and changeable molds, appear to be a promising choice for achieving manufacturing economic sustainability. They represent an effective way to save resources and reduce labor costs and setup times. This paper explores the evolution of molds used in manufacturing, from the old models to the current reconfigurable ones through a state-of-the-art analysis of academic research and solutions implemented by industry. Conclusions and insights are presented.

Keywords: Reconfigurable molding; Mold evolution; Discrete pins; Economic sustainability; Literature review.

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1. Introduction

The current manufacturing environment is moving from mass production to mass customization, characterized by small batches and large product variety [1]. This modern trend is in contrast with some manufacturing process such as molding, typically employed for mass production because of the long changeover time of the molding machines. In particular, traditional molds are often dedicated and expensive. They are manufactured for a single product design and can be used for the production of that specific product. Any change in product design makes the mold unsuitable and a new one has to be made. The introduction of flexibility and reconfigurability principles in the molding machines is necessary to allow rapid mold redesign and enable mass customization of products in day to day operations [2]. Flexible and reconfigurable molding processes seem to be a promising choice to achieve the manufacturing economic sustainability and represent an effective way to save resources and to reduce labor costs and setup time. Current literature proposes two main solutions to include flexibility and reconfigurability in the molding machines: the first is the use of modular adaptable molds and the second is the use of matrices of discrete adjustable pins. From a managerial view point, in the last few years, some industrial companies adopted the pin technology (e.g. BMW) but the solution most used by Industry is the so-called Master Unit Die (MUD) Quick-Change System that enables fast production changeovers for maximum efficiency with attractive costs. Starting from this background, this paper explores the evolution of molds used in manufacturing, from the old dedicated and rigid models to the modern flexible and reconfigurable ones through an in-depth state-of-the-art analysis of both academic research and solutions implemented by Industry. The schematic research perspectives in Fig. 1 helps categorize and structure the findings of the presented literature survey. The remainder of this paper is organized as follows: Section 2 introduces the research approach, and Section 3 discusses the findings of the literature survey. Finally, Section 4 concludes the paper with final remarks and future research opportunities.

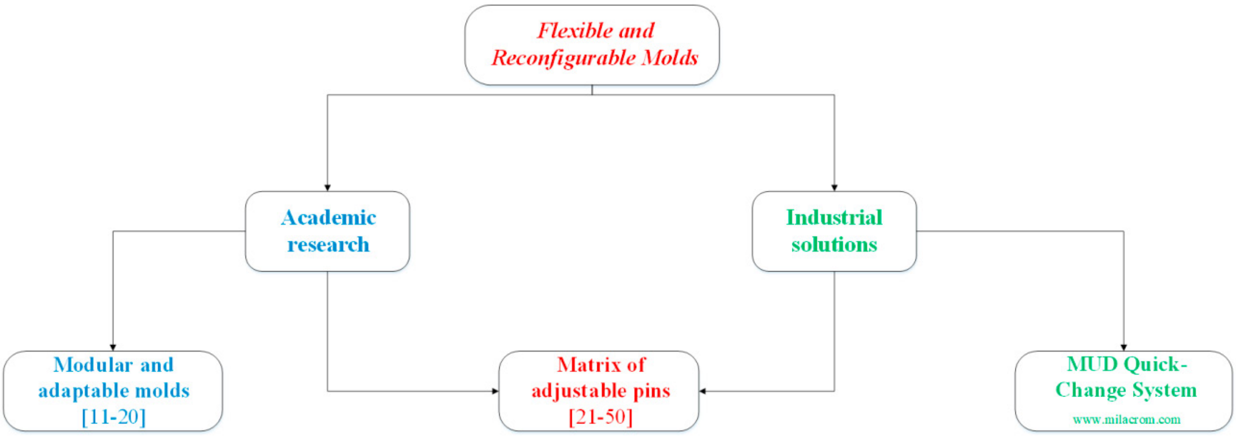

Fig. 1. Schematic of flexible and reconfigurable molds research perspectives.

2. Research method

An in-depth literature survey related to flexible and reconfigurable molds is carried out. The time frame for the review extends from 1892 to 2017. This literature search is conducted using the following databases: Elsevier, Taylor & Francis, Springer, Emerald Insight and ASME. In addition, a library-based search is conducted to include recent master and Ph.D. dissertations. A total of 50 documents are reviewed, including patents, journal papers, conference papers as well as master and Ph.D. dissertations (Fig. 2). Of these, 10 patents published between 1892 and 2004 are reviewed. Furthermore, 30 articles published in international journals are reviewed (1969-2017) as well as 3 conference papers (2009-2017) and 4 master and Ph.D. dissertations (2010-2015).

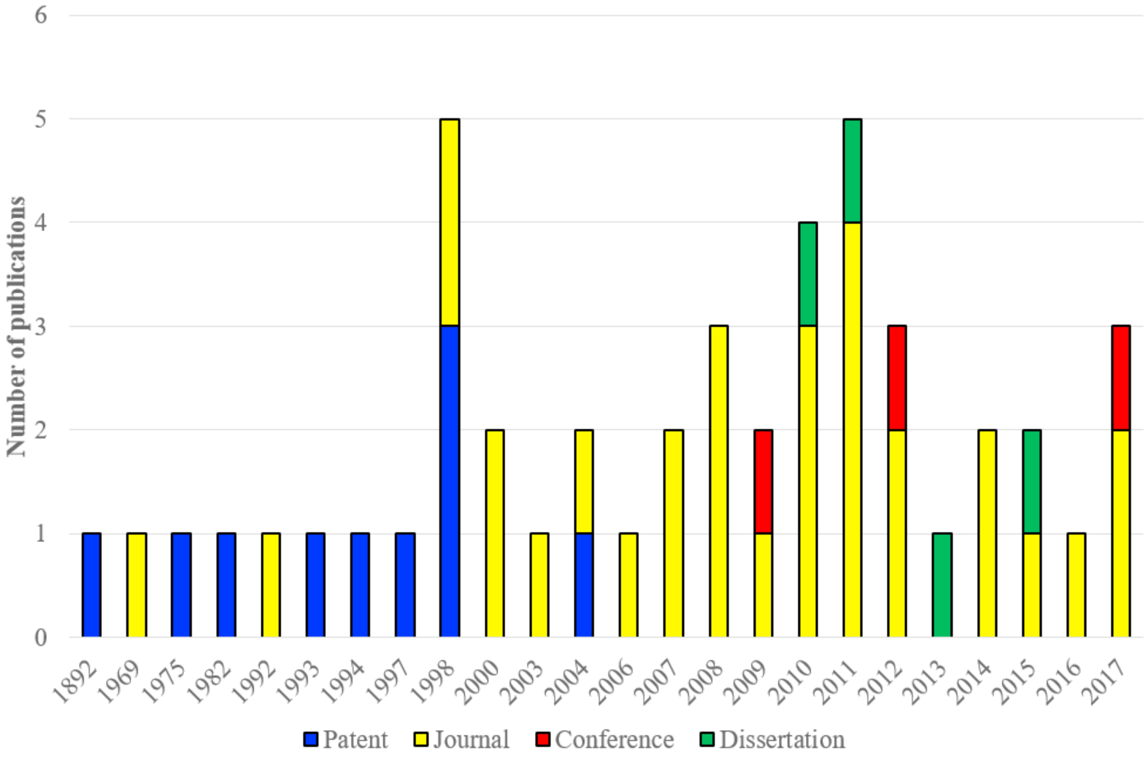

Fig. 2. Reviewed documents classification.

Fig. 2 shows that patents (blue bars) represent the oldest documents, almost all released in the United States of America while journal papers (yellow bars) represent the most published type of documents. In the last few years, some master and Ph.D. dissertations are published. This phenomenon proves the increasing interest by researchers in flexible and reconfigurable molds as well as the desire to undertake a long-term research path on the topic.

3. Literature survey

3.1 The need for flexible tooling

Current changes in manufacturing are characterized by aggressive competition on a global scale and rapid changes in process technology. These trends require the creation of production systems and tools which are easily upgradable and reconfigurable by themselves and into which new technologies and functions can be readily integrated [3-7]. In particular, the advent of the mass customization paradigm has led to high demand for flexibility and adaptability of both manufacturing technology and systems [2] to reach the manufacturing economic sustainability and to overcome the main limitations that affect traditional manufacturing processes (e.g. high changeover/setup time and short machine runs) [8]. Focusing on molding, this type of manufacturing process is commonly employed for mass production since it is characterized by long changeover/setup time. However, dynamic product life cycles and the increase in the number of product variants have inevitably led to a decrease in batch sizes. Reconfigurable tooling appears to be a promising choice to satisfy market requirements, save resources and reduce labor costs and setup times. The first design of a discrete reconfigurable molding tool emerged in the mid 1800's. In 1892 and in the following years, several versions and improvements of a manually adjustable spring-forming press were patented, in response to the demand for vehicular suspension springs [9]. Nowadays, the design and manufacturing of dies and molds still represent a key activity in the entire production chain because most of the mass-produced parts are formed using processes that employ dies and molds [10]. Factors like quality, cost and lead time of molding affect the economic sustainability of producing a huge number and variety of components, hence, the implementation of flexible tooling systems and the introduction of flexibility and reconfigurability principles in the molding machines are mandatory targets to consider. Current literature proposes the use of modular adaptable molds and the use of matrices of discrete adjustable pins to introduce flexibility and reconfigurability in such machines. Industrial companies use the MUD Quick-Change Systems. Fig. 3 shows the trend in terms of number of publications about the two solutions proposed in the literature. Such trend confirms that the use of matrices of discrete adjustable pins is the solution most explored by researchers. The following sub-sections examine each of these solutions.

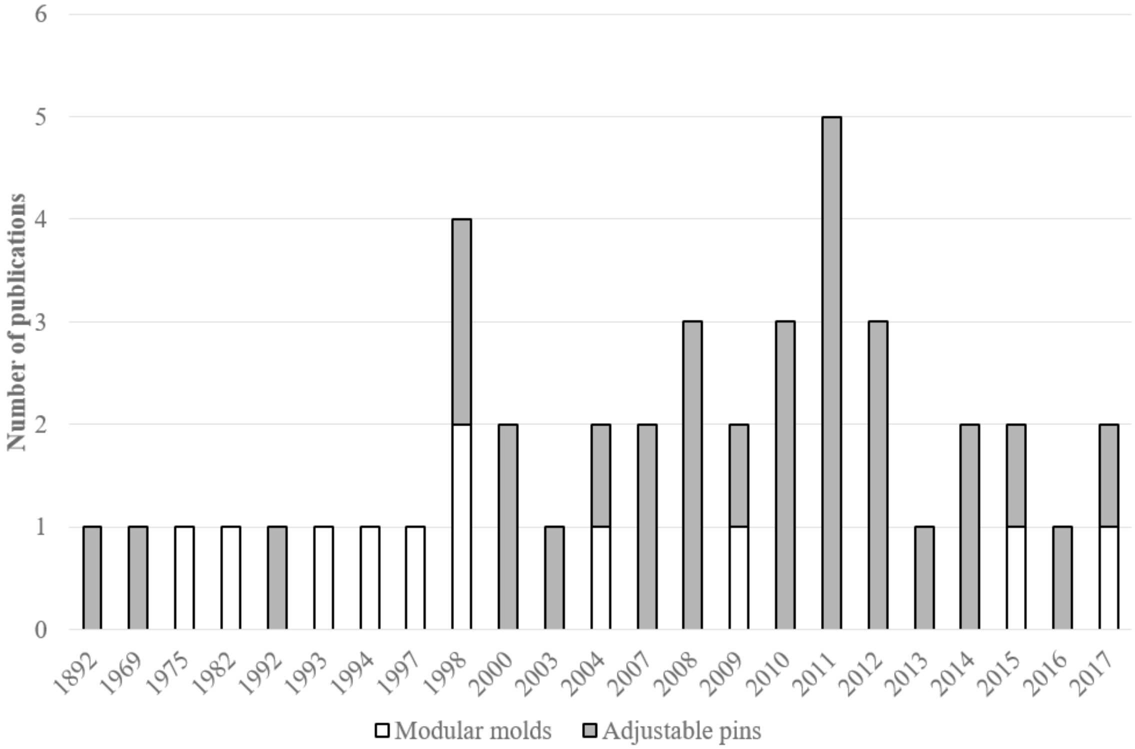

Fig. 3. Literature trend: modular molds and matrices of adjustable pins.

3.2 Modular and adaptable molds

The use of modular and adaptable molds is widespread in the literature. Taketa [11] proposes a mold apparatus characterized by a fixed mold base and removable and replaceable cores and cavities, eliminating the need to provide a new mold base for every new product. Implementing this solution, the mold cost is reduced as well as the machine down time and the storage costs since only the core and cavities need to be stored. Platte [12] and Collette et al. [13] released patents for the design of modular molding machines for the production of plastic bottles. The mold proposed by Platte incorporates adjustable inserts, which may take various forms and include means for locking insert adjustment. The model proposed by Collette et al. [13] is characterized by adjustable height shims provided between the upper and the lower panel sections to adjust the volume and height of the beverage bottles. Noritake et al. [14] introduce a molding machine having a set of exchangeable sub-molds, each of which is detachably mounted in each of the sub-mold hollows. Pratt et al. [15] introduce a machine characterized by adaptable mold bases. The ability to interchange and reconfigure the mold base minimizes the tooling costs and adds design flexibility to the tool. Vanderlande [16] and Vanderlande [17] respectively propose a reconfigurable mold with travelling ejector system and travelling separator assist. Such systems are characterized by movable mold bodies that can be automatically repositioned with respect to each other to mate different mold cavities for molding different parts. Marson et al. [18]

designed a precision mold for micro-injection molding of truly three dimensional microfluidic devices. The proposed mold uses the concept of replaceable cavities to enable the flexible development of the complex microfluidic device. The overall goal is to reduce machining time and production costs. Pugliese et al. [19] propose a preliminary design methodology to help designers decide which mold configuration is suitable to produce a molded part family. The purpose of the proposed methodology is to define how to arrange the components of the modular mold and how to combine them to carry out product functions. In such a methodology, the need to obtain molds with greater reconfigurability is achieved by considering the different mold components as potential tools to promote and/or enhance the characteristics of reconfigurability of the mold. In this study, the mold cavity is considered as the only reconfigurable component. The proposed modular mold prototype is in Fig 4. Moustafa et al. [20] conduct a study to investigate the use of non-metal thermoforming inserts to reduce mold manufacturing time and cost.

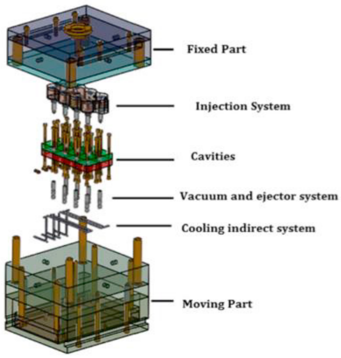

Fig. 4. Modular mold, derived from [19].

3.3 Matrix of discrete pins

The existing literature on reconfigurable molding proposes the use of discrete pin tooling systems [21-23]. Such systems are characterized by one or more matrices of discrete adjustable pins, arranged to form a cavity having the same shape of the object to be molded (Fig. 5). In this way, different tool configurations can be achieved by changing the pin locations relative to each other, which eliminates the need for multiple tools.

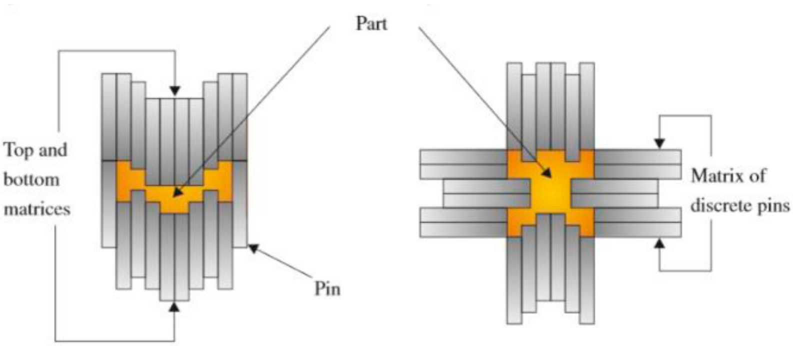

Fig. 5. Cross-sectional view of a reconfigurable mold tool, derived from [22].

The development of a reconfigurable pin tooling system is a complex procedure as it involves many aspects of the system that need to be integrated (e.g. design, process planning, manufacturing and assembly) [24]. The focus of current literature is on pin design in terms of pin shape and density, pin actuation methods and tooling surface treatments. Regarding the pin design, Walczyk and Hardt [25] state that:

- the pins should have a uniform cross-sectional shape, size and length to reduce the cost and lead time of fabrication;

- the pins should withstand the buckling and bending forces produced during application;
- a matrix of identical pins should be easily clamped into a rigid tool;
- the cross-section of the pins should be as small as possible to allow an adequate tooling shape fidelity.

Researchers propose four main types of pins cross-sectional shape: square, hexagonal, round and threaded pin [25] (Fig. 6). The square and hexagonal shaped pins can be densely packed into a consistent matrix without gaps between adjacent pins. There are some small gaps among the closed pack round pins and threaded pins. Each round pin in reconfigurable tooling is normally made into a hydraulic or pneumatic cylinder allowing it to be individually actuated [24]. Pin density represents another key aspect of pin design. Two main types of pin density models have been proposed: uniformly spaced or closed-packed matrix of pins (Fig. 6). In both configurations, the reconfigurable pins are adjusted to the desired shape and then locked into rigid tooling.

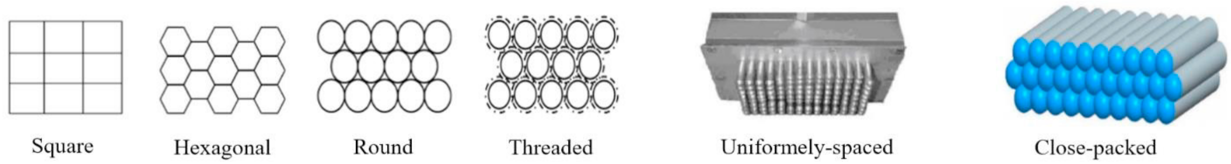

Fig. 6. Pin shape and density classification.

In the close-packed configuration, the adjacent pins can easily support each other to withstand high forming loads thanks to the limited space between the pins. However, in such a configuration, the individual actuation of each pin becomes difficult. In the uniformly-spaced configuration, pins can be easily actuated because of the distance between the pins. At the same time, the lack of a direct structural support from adjacent pins limits the forming loads that such a tool can withstand. Findings of the literature survey show that most of the applications and prototypes of reconfigurable molds based on pin tooling system developed so far adopts square and hexagonal pins arranged in a close-packed configuration [2, 21-49] because of the benefits provided by such systems while only few applications adopts round pin shapes [23, 27, 30, 43, 50].

The key to reconfigurable tooling is to move a matrix of pins upward or downward to positions determined by component geometry. Therefore, the actuation of the pin movement is critical for the reconfigurable tooling using discrete pins. Several pin actuation methods including manual, mechanical (e.g. leadscrew-driven), hydraulic or pneumatic and numerically controlled have been developed by researchers to set the shape of the pin matrix prior to it being clamped into a rigid tool. Another key aspect to consider is that the presence of the pins inevitably creates a discrete surface. This surface limits its applicability and a smooth method is required to suppress dimpling and wrinkling caused by the discrete pin tips. Several smoothing methods including the use of a deformable interpolating layer e.g. elastic, elastomeric, rubber, etc., deformable pin tips and machining (milling pin top ends or hardenable surface formed by filler) have been discussed by researchers.

The overall results from the literature survey on reconfigurable pin tooling stress that square pins close-packed into a consistent matrix represent the most used design configuration since it minimizes the gaps between adjacent pins and allows withstanding high forming loads. Various methods are used for the actuation. The use of elastomeric interpolating layers is widespread to smoothen the tooling surface.

3.4 Solutions implemented by Industry

The industrial interest towards reconfigurable and flexible tooling began in the late 1980s for the production of composite aerostructures and such technologies represent still today a great challenge in Industry.

In the last few years, reconfigurable pin tooling technology is used in some industrial companies [51]. In particular, this technology is now implemented by BMW AG (Munich, Germany) for the production of its 7 Series cars. Furthermore, it is recently commercialized by Adapa and Curve Works to eliminate recurring tooling costs and, as a result, make production of one-off, 3D curved panels affordable. The company Surface Generation Ltd. (Lyndon, UK) applied the so-called Subtractive Pin Tooling (SPT) technology to composites moldmaking. Instead of milling a tool from solid metal billets, SPT manufactured and delivered precision molds in days rather than months. The Delft University of Technology (TU Delft, Delft, The Netherlands) and the University of Birmingham (Birmingham, UK) develop in collaboration with several industrial companies the 2014-2017 *Automated Manufacturing Process Integrated with Intelligent Tooling Systems* (AUTOMAN) project. The aim was to develop the world's first fully reconfigurable pin-based tooling system with in-process sensing and computer control. Projected benefits were a 50-100% in manufacturing efficiency, cost savings of 80%, and 30-50% material and energy savings over the product lifecycle. By project end, AUTOMAN built and demonstrated a multi-pin tool as well as a numerical model for simulating forming of sheet metal, including predictions of forming limits and springbacks. However, additional development is needed, including further software and sensing integration, transfer to industry-specific applications and scale-up to large panels.

However, the solution most used by industrial companies is represented by the Master Unit Die (MUD) Quick-Change System that enables fast mold reconfiguration and production changeovers for maximum efficiency at attractive costs. This approach uses an unlimited number of companion insert molds easily interchanged within a single MUD Quick-Change frame. The frame remains in the machine during the mold changeover and most changeovers take less than five minutes.

4. Conclusions

The dynamic market demand, the short product life cycles, the need for flexibility and the increased variety of customized products force industrial companies to move from mass production to mass customization. The main advantage of such strategy is to provide different goods to customers at the same quality and price of the mass-produced products. This modern trend presents a challenge to manufacturing processes, such as injection molding which are usually characterized by high changeover time since they are employed for mass production to avoid short runs of the machines and to lower production costs, with the overall goal to guarantee the manufacturing economic sustainability. This paper explored the evolution of molds used in manufacturing, from the old dedicated and rigid models to the modern flexible and reconfigurable ones, through an in-depth literature survey with a focus on academic research (i.e. modular adaptable molds and use of matrices of discrete adjustable pins) and on solutions implemented by Industry (i.e. MUD Quick-Change System). This study provides researchers, industrialist and practitioners with a richer knowledge on flexible and reconfigurable molding. The challenge of achieving flexible and reconfigurable molds for small and medium production volumes of complex product shapes which minimize changeover times and operating costs will continue to stimulate future research in this important field.

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