Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 13 (2017) 102–108

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

Manufacturing Engineering Society International Conference 2017, MESIC 2017, 28-30 June 2017, Vigo (Pontevedra), Spain

Direct rapid tooling for polymer processing using sheet metal tools

D. Afonso[a,b,]*, L. Pires[a,c], R. Alves de Sousa[b], R. Torcato[a,c]

[a]*School of Design, Management and Production Technologies Northern Aveiro, University of Aveiro, Oliveira de Azeméis, Portugal*
[b]*TEMA: Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, Aveiro, Portugal*
[c]*CICECO: Centre for Research in Ceramic and Composite Materials, University of Aveiro, Aveiro, Portugal*

Abstract

The rapid tooling notion has been discussed since the beginning of the additive manufacturing processes. The concept consists on using fast manufacturing technologies to develop tools to process other materials. New incremental sheet metal forming processes operation allows a parity to the former rapid prototyping perception, and so feasibly considered a smart manufacturing process. This processes encounter industrial applications not only in prototyping and part manufacturing but also in tool development and fabrication.
This paper discuss the fundamentals of the rapid tooling concept and presents four examples of the use of incremental forming for the development of sheet metal moulds. The research concludes with a proof of concept for the use of rapid sheet metal tools for processing thermoplastics and thermosets. The use of incremental forming as a rapid tooling technology contributes to decrease the time to market, decrease tooling cost and increase tooling complexity and consequential part design freedom.

Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.

Keywords: Incremental Sheet Forming; Rapid Tooling; Smart Manufacturing

1. Introduction

Product development takes advantage on the use of computer aided design (CAD) systems to define the geometry and its various dimensional characteristics. Besides, the products feasibility can be predicted using computer aided

* Corresponding author. Tel.: +351 256 666 960; fax: +351 256 666 970.
E-mail address: Dan@ua.pt

2351-9789 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.
10.1016/j.promfg.2017.09.016

engineering (CAE) software for the analysis of product performance and for the simulation of manufacturing processes without the need of physical prototypes. While this iteration strongly improves the probability of success, in many cases a physical assessment of the real component is still needed. This often requires the creation of prototypes and tools to be produce, becoming one of the most time consuming and costly phases in the development of new [1, 2].

Rapid tooling (RT) is the term used to the production of tools or tooling components with reduced lead time, as compared to conventional manufacturing techniques, through direct or indirect processes. The direct processes consist in use one technology capable to reproduce tools with similar properties to the actual tools. The indirect processes involve the use of more than one technology, first to produce a pattern and second to obtain the actual tools through the pattern. Besides, the tooling process can also be classified according to the used materials. If the tooling material can only be used to produce few production copies before it wears, such process is referred as soft tooling. Hard tooling on the other hand involves the production of tools capable of producing thousands of parts [1-3].

The leading characteristics of a rapid tooling process should ensure: (i) Tooling time is much shorter than for a conventional tool. Typically, time to first market ready products is below one-fifth that of conventional tooling; (ii) Tooling cost is much less than for a conventional tool. Cost can be below five percent of conventional tooling cost; (iii) Tool life is considerably less than for a conventional tool; (iv) Tolerances are wider than for a conventional tool and have worst surface finishing [4].

Conventional manufacturing technologies, such as casting and injection moulding, are often used in the manufacture of products. These technologies required tools or tooling components (e.g. moulds, inserts) that need to be development, especially as used for a particular purpose or new product. Machining technologies and heat treatments, frequently used, augments time and costs in product development process. Sometimes, these factors invalidate the low volume productions and limit the market introduction of custom solutions or niche products [1, 5].

The adoption of rapid manufacturing technologies allows create skills on production of tools for low volume products production, as wells as reduce product costs and make time to get products to market faster. These technologies are also applied to test and valid projects with the manufacturing of 3D physical models. These steps allows to detect errors early in the product development process and designing better products. Improvements or tools modifications are sometimes required during the manufacturing process. The rapid manufacturing of parts and tools can benefit both the product development and production set up, allowing the achievement of faster solutions [1].

2. ISF as a rapid tooling process

Incremental sheet forming (ISF) is a sheet metal forming technique where a sheet is formed into the final workpiece by a series of small continuous incremental deformations. The process is controlled entirely by CNC processes and no die is needed as is in traditional sheet metal forming. The removal or simplification of the die in the manufacturing process decreases the cost per piece and improves turnaround time for single parts or low batch production runs. On the other hand, the differences in the forming principle lead to a loss of accuracy and differ the possible achievable part design. Incremental forming processes can be considered as rapid prototyping as they are well-suited for small-batch production, and rapid production of service parts and may reduce time to market [6, 7].

Mainly due to their novelty and the technologies used in most processes, the RT haven been majorly associated with additive manufacturing (AM), often called fast freeform fabrication. ISF processes can be seen as rapid prototyping processes [7], and so, also considered rapid manufacturing methodologies. Besides, being compatible with flexible manufacturing systems, with parts manufactured from CAD models without considerable dedicated tools in short time, ISF processes can be seen analogously to AM technologies. Thus, it is reasonable to apply the RT term when describing the fabrication of tools for different industrial processes using ISF techniques.

Some conventional polymer manufacturing processes involve low pressure and temperature for moulding materials (e.g. thermoforming, rotomoulding, hand lay-up, compression moulding). In these cases, the mechanical requirements are low and the operation benefits from low mould thermal inertia. In such a way, ISF technologies finds an interesting applicability for the moulds production from sheet metal, attaining low cost tooling with high strength over weight ratio.

3. Development of sheet metal tools by SPIF

A large variety of ISF principles have been developed in the past years. One of the most common process is Single Point Incremental Forming (SPIF). SPIF uses one single CNC controlled tool to form a sheet clamped along the edges and supported peripherally by a backing plate. The forming tool, typically a spherical punch, fallows a continuous peripheral movement from the part boundary to the center while increasing the forming depth and shaping the blank to a free form design. During this process thinning occurs at the sheet thickness, as represented in Fig. 1. The final thickness can be estimated by the sine law, where $tf = t0 \times \sin(90-\alpha)$. Guidelines for the possible part design have been defined, where the most important feature is the maximum wall angle [8, 9].

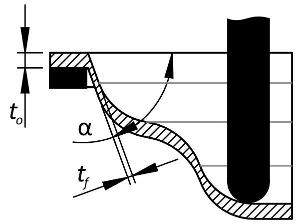

Fig. 1. Thinning during the SPIF process.

Within the goal of validating the use of sheet metal moulds manufactured by ISF techniques, the research tested different hard direct rapid tools for processing both thermoplastic and thermoset materials. Tests are performed using 2 mm thickness aluminium alloy 1050-H111 sheet with a Young Modulus of 71 GPa, a Poisson ratio of 0.33 and a yield strength of 103 MPa. The material allows a SPIF operation up to a 70º wall angle, with the material achieving a yield value of 130 MPa due to strain hardening.

A reference geometry is designed for the definition of the rapid tools, based on a drafted volume with a maximum wall angle of 70º with a projected area of 180 × 180 mm. A lower slope side wall is included to avoid full symmetry. The geometry uses flat faces with sufficient area to cut mechanical test specimens.

3.1. Processing thermoplastics

The thermoplastic materials are largely used due to their shaping capabilities, interesting mechanical performance and recyclability. A large variety of processes exist, where a differentiation can be done in what regards the moulding pressure. SPIF is used for the manufacture of hard tools for vacuum thermoforming and rotomoulding operations. Fig. 2 (a) present the positive thermoforming tool inside the machine and Fig. 2 (b) shows the open rotomoulding tool filled with thermoplastic powder mounted on the rotational moulding system.

For the thermoforming operation, two approaches where fallowed, defining both a positive and a negative mould. Since the ISF processes are mainly suited to shape container type parts, the definition of the negative tool cavity is straightforward. For moulding operation, the sheet metal part is peripherally supported in a drafted MDP support box. The definition of the positive mould core is influenced by the sheet thickness. Thus, the sine law is used to define the reverse cavity geometry. The sheet metal part is supported in a MDF board for the thermoforming process. In what regards the mechanical behaviour of the mould, the 2 mm initial thickness sheet is able to support the vacuum load [10]. Thinner sheets or larger tools may need additional support, either by a frame grid or a porous mixture [11].

The rotational moulding part is design from the reference geometry with the addition of an open kiss-off structure. This linkage between two part sides is common in rotomoulded parts to serve as a structural reinforcement and can lead to only a contact point or an open window. Two sheet metal parts are used to define the tool with the closing guiding and clamping done using screws. As the SPIF operation leads to an unavoidable small radius at the part top, high temperature epoxy mass is used to improve the mould accuracy. The same process can be used for a complete coverage to improve surface finishing as well as the geometric accuracy. From the mechanical point of view, the sheet metal is capable of support the moulding loads. In what concerns the thermal behaviour, the thickness differences have a negative impact on the temperature distribution, nevertheless compatible with the rotomoulding process [12].

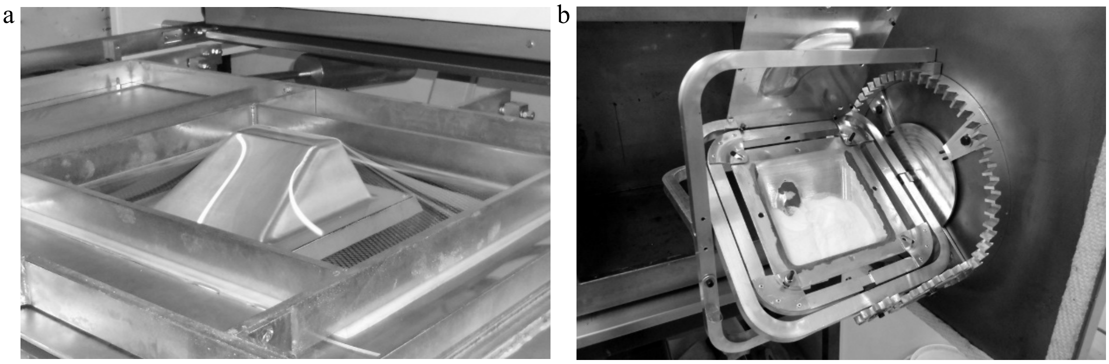

Fig. 2. Low pressure thermoplastics manufacturing processes with rapid sheet metal tools: (a) thermoforming; (b) rotomoulding.

The manufacture of the sheet metal parts is performed on the SPIF-A machine. [13] The forming operation uses a 12 mm spherical tip punch in a single stage helical tool path strategy with 0.5 mm vertical increment. The operation involves the cut of a dedicated backing plate for each part. Considering the backing plate cut, blank cutting, the forming itself and finishing and assembly tasks, the thermoforming and rotomoulding tools are developed in 1h30 and 2h30 respectively, with and energy consumption of 6.6 kW.h and 11.0 kW.h and material cost of 8€ and 20€.

No significant difference is found when operating with sheet metal moulds instead of conventional tools. In both technologies, the material is shaped in the same way as when operating with conventional tools. In the vacuum assisted thermoforming operation, the low weight prevents the mould from descending due to a slight stick to the formed part. Nevertheless, the part releases with ease from the moulds. In the rotomoulding operation, the material shrinkage during the cool down promote an easy demoulding from both the aluminium mould surface and the epoxy mass.

3.2. Processing thermosets

Where the thermoplastics have their applicability mainly on large volume production, a lot of small batches of unique parts take advantage of the use of thermoset materials. In these applications, thermosets are often used as a binder resin in composite materials, allowing not only the production of smaller batches but also achieving distinctive material properties and part behaviour. Sheet metal tools are developed to be used in fiberglass hand lay-up operation and in cork compression moulding, as presented in Fig. 3 (a) and (b). The two new parts are designed from the reference geometry with the addition of reinforcement indents. The rotational moulding tool is also used in rotocasting operations.

The open mould for contact moulding of composites is defined in a negative configuration. Being a simple container, the mould design is straightforward from the part geometry, with reinforcement indents in the lower slope and the opposite walls. From the mechanical point of view, a thin metal sheet can support the moulding loads. Nevertheless, the 2 mm thickness sheet is used to allow a feasible forming operation due the maximum wall angle. The mould assembly uses a MDF support box to facilitate the lamination operation.

The cork part is designed with indents in all the side faces and a variable thick thickness. A two-piece sheet metal mould with a cavity and a core part can define the part geometry. However, due to the low density of the uncompressed cork granulate, the cavity volume is not sufficient to accommodate all the material mixture. Thus, a frame box with vertical extended walls is added to the cavity to increase its volume. This frame box is also used to lock the core side of the mould in place under pressure to cure the binder in an oven. From the mechanical point of new, the sheet thickness is at the limit of operation. A support box is sized to allow the cavity part to be supported both by its boundary and its bottom. The use of reinforcements or filling is recommended. From the thermal point of view, the low thermal inertial benefit’s the heat and cool time for the binder curing process [14].

a b

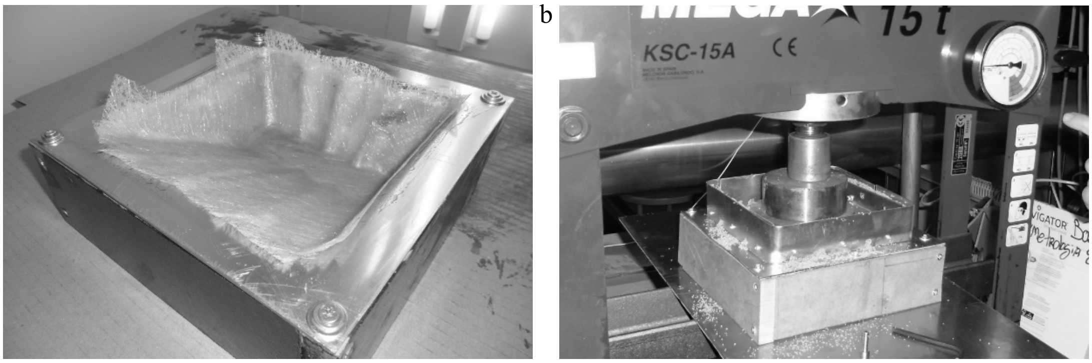

Fig. 3. Thermoset manufacturing processes with rapid sheet metal tools: (a) hand lay-up; (b) cork compression moulding.

The tools development is performed in an analogous method then the one developed for the thermoplastic processing. Apart from the container type parts, the cork compression mould uses a flange type part to define the frame box and a manually bent height extension. The hand layup and compression moulds manufacture take respectably 1h30 and 4h30 to produce, with an energy consumption of 9.1 kW.h and 17.2 kW.h and a material cost of 8€ and 20€.

In what concerns the mould operation, the hand lay-up procedure is performed without any difference from the use of conventional moulds. The cork compression moulding is performed with a 1:2 compression ratio. The moulding operation leads to a slight loss of material and miss agglomeration of material near the part edge due to the gap between the frame box and the core side of the mould.

3.3. Moulding operation and parts analysis

All developed tools where used for multiple tests, validating not only the possibility of use but also the short term behaviour. Fig. 4 shows a group of parts manufactured with sheet metal tools: from left to right a hand lay-up fibre glass part, an agglomerated cork part, a rotomoulded polyethylene part and an acrylic thermoformed part. All the manufactured parts are measured to analyse accuracy and the part quality is evaluated by visual inspection. The four developed tools succeed to mould the specific parts with relative success. Table 1 summarizes the qualitative analysis of the results.

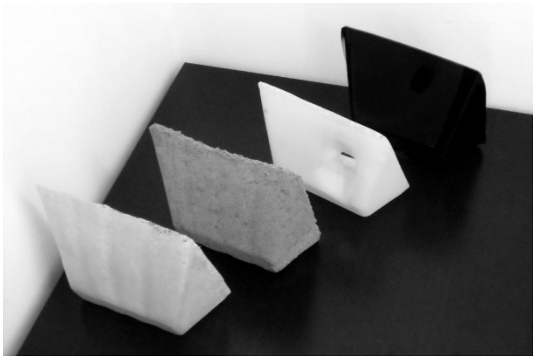

Fig. 4. Parts manufactured with sheet metal rapid tools.

In what concerns accuracy, the sheet metal parts are formed within a general ±2 mm error, with maximum deviation near the top boundary of -5 mm. The accuracy of the parts is both influenced by the tool accuracy and the moulding process itself. Generally, the parts global accuracy is within a ±3 mm error. However, some parts reach their greater deviations in the order of 10 mm at some points close to the parting line. Still, this extreme deviation is only found on specific points, due to inaccuracy of the mould but mainly to issues in the moulding operation itself.

The definition of the part detail is influenced by the sheet metal surface and mould geometry. All the developed parts reach the global designed shape with success. However, the part minimum detail is limited by the SPIF part feasibility and mould finishing. On the open moulds or single side moulds, the minimum details in the finished part is only limited by the minimum achievable feature trough SPIF. On the multiple piece tools, the part detail is also affected by the parting line. On the rotational moulded parts, the use of epoxy filling mass reduced parting line issues. On the cork compression moulding tool, the gap between the mould sides have negative impact on the edge definition.

The surface quality of the parts is mainly influenced by the sheet metal surface. The sheet metal scratches due to the punch contact and skinning have a negative influence on the moulded parts. This effect is mainly noticeable in the technologies and materials capable of defining the smaller details.

Regarding the tool performance, the moulding operation runs in a similar way as when using conventional tools. The processes that deal with temperature benefit from the low thermal inertia to speed up the process. In the rotomoulding process the all process is faster. In the thermoforming and compression moulding processes, the cooling time for part release is faster. From the mechanical point of view, only the cork compression moulding features issues. Due to the higher moulding pressure, the tool suffers a small permanent deformation. The use of reinforcements or support filling could prevent this difficulty.

Table 1. Comparative analysis of the moulded parts and tools.

Manufacturing Process	Part accuracy	Part detail	Surface quality	Tool performance
Thermoforming	Fair	Poor	Fair	Good
Rotomoulding	Good	Poor	Fair	Good
Rotocasting	Fair	Poor	Poor	Good
Hand layup	Good	Fair	Fair	Good
Compression moulding	Fair	Good	Good	Poor

4. Conclusions

The research validated the use of SPIF as a RT process with some proof of concept tests. Sheet metal tools have enough stiffness and strength to support the moulding forces from low pressure manufacturing processes. The low thermal inertial benefits the temperature related manufacturing processes, speeding up the operation time. The achievable part quality, both regarding accuracy, detail and surface quality, is compatible with a large number of product applications, mainly when dealing with low volume production.

Sheet metal tools are fabricated using a smart manufacturing process from CAD models. The mould geometry definition can be ensured using the sine-law for prediction the final thickness. This models may be used not only to support the manufacturing but also to simulate the tools behaviour. The fabrication is achieved in a short time, with reduced energy consumption and material cost. The use of standalone sheet metal moulds developed by SPIF allows to start manufacturing parts within a few hours.

The use of structural reinforcement or support of the mould can benefit its performance, mainly when dealing with higher pressures or larger parts. The achievable part quality can be improved by mould finishing operations. The use of filling masses can profit both the mould accuracy and surface finishing at the cost of longer manufacturing time and hand skilled dependent. Over thickness of coverage mass should be avoided to prevent harming the thermal behaviour of the tools.

From the analysed case studies, the use of SPIF sheet metal moulds has greater advantages for the development of rotomoulding and hand layup tools. It is also considered that the process has the potential to develop hard direct rapid tools for other technologies such as other contact moulding alternatives and casting with multiple materials.

References

[1] P. D. Hilton, P.F. Jacobs, Rapid Tooling: Technologies and Industrial Applications, first ed., Marcel Dekker, Inc., 2010.
[2] A. Equbal, A. Kumar Sood, M. Shamim. J. Manuf. Ind. Eng. 14 (3-4) (2015) 1-9.
[3] P. Vasconcelos, F. Lino, R. Neto, M. Vasconcelos, Design and rapid prototyping evolution. RPD 2002 - Advanced Solutions and Development conference, 2002.
[4] E. Tackett, Rapid Tooling. Saddleback College Advanced Technology Center.
[5] S. Smith, G. C. Smith, R. Jiao, C. H. Chu, J. Intell. Manuf. 24 (5) (2013) 877-885.
[6] S. Tabibian, M. Najafabadi, Int. J. Eng. Adv. Technol, (2014) 24-28.
[7] M. Skjoedt, N. Bay, T. Lenau, “Rapid Prototyping by Single Point Incremental Forming of Sheet Metal”, PhD thesis, Technical University of Denmark, 2008.
[8] D. Adams, J. Jeswiet, J. Eng. Manuf. 229 (5) (2015) 754-760.
[9] D. Afonso, R. Alves de Sousa, R. Torcato, Defining design guidelines for single point incremental forming - rules to a good design of container and tunnel like parts manufactured by incremental forming. Sustainable Smart Manufacturing Conference, 2016.
[10] D. Afonso, R. Alves de Sousa, R. Torcato, Testing single point incremental forming molds for thermoforming operations. The 19th International ESAFORM Conference on Material Forming, 2016.
[11] R. Appermont, B. Van Mieghem, A. Van Bael, J. Bens, J. Ivens, H. Vanhove, A.K. Behera, J. Duflou, Proceedings of the 5th Bi-Annual PMI Conference, pages 383-388, 2012.
[12] D. Afonso, R. Alves de Sousa, R. Torcato, Testing single point incremental forming molds for rotomoulding operations. The 20th International ESAFORM Conference on Material Forming, 2017.
[13] R. Alves de Sousa, J. Ferreira, J. Farias, J. Torrão, D. Afonso, M. Martins, Struct. Eng. Mech. 59 (5) (2014) 645-660.
[14] D. Afonso, R. Alves de Sousa, R. Torcato, A cost-effective methodology to perform customized moulding of cork agglomerates, Second Cork in Science and Applications Conference, 2017.