Technological and Economic Comparison of Additive Manufacturing Technologies for Fabrication of Polymer Tools for Injection Molding

Achim Kampker[1], Bruno Alves[2], and Peter Ayvaz[1(✉)]

[1] RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany
p.ayvaz@pem.rwth-aachen.de
[2] Ford Motor Company, Wernigerode, Germany

Abstract. This paper investigates the technological and economic potential of 10 different AM materials manufactured with four different AM technologies for the use of tool production for injection molding in small series applications. Therefore, experimental trials with three different injection molding materials with increasing manufacturing difficulty in terms of resulting tool loads are conducted. Tool wear, resulting part quality and tool manufacturing cost are taken into account for potential evaluation. A concrete selection of the most suitable materials for further investigation is given.

Keywords: Additive tooling · Injection molding · Rapid tooling

1 Introduction

The increasing market dynamic, competition and an uncertain environment poses challenges for manufacturing companies [1]. Shorter product lifecycles and more product variants with an increasing technical complexity require shorter and more frequent product development and ramp-up phases [2]. For all tool-bound manufacturing processes this leads to demanding requirements for tool manufacturing as costs and time–to-market need to be reduced consistently [3–5]. New process technology combinations, such as additive tooling for injection molding are used to decrease costs and shorten time-to-market of polymer components [6].

Over the last two decades, the concept of additive manufactured polymer injection molding tools has been further developed to meet these new requirements of increased product variety and decreased lead times in polymer part production within product development [7, 8]. There are generally two approaches to integrate additive manufacturing into tool production within product development [9, 10]: Indirect tooling makes use of additive manufacturing for master pattern production to manufacture the tool in a subsequent second production step, mostly some form of casting. Direct tooling makes use of additive manufacturing to produce the tool immediately without a second manufacturing step except some form of post processing for quality enhancement. Comparing the process chains of these two approaches, it is evident, that the

direct approach generally requires less process steps and hence offers an inherent benefit in terms of lead times which is why this paper focuses on the direct approach.

Prior case studies on the use of additive manufactured polymer tools for injection molding have investigated the technological potential with respect to resulting part quality as well as tool life of different tooling materials in comparison to conventionally manufactured tools for different applications. Reference [11] shows, that the PolyJet-Material Fullcure 720 is able to withstand 20 cycles compared to 10 cycles of an Al2O3 filled epoxy resin during injection molding using a PLA. The potential use of resin coated 3D printed polymer tools using the PolyJet Material "Digital ABS" was demonstrated in [12]. Another investigation of "Digital ABS" as tool material showed, that the dimensional stability and the surface roughness of the printed tool remained stable over a period of 50 cycles using PP as injection material [13]. Further, the resulting mechanical part material properties deviated little compared to the material properties from parts manufactured in a conventional steel tool [13]. The thermal conductivity behavior of "Digital ABS" as tool material was found suitable for small series production of nucleated PLA resulting in similar thermomechanical part material properties as in temperature controlled steel tools for mass production [14]. "Digital ABS" as tool material once more was investigated in a comparative study using PP as injection material. Compared to a conventional steel tool and a direct metal sintered tool, the PolyJet tool lasted significantly less cycles and resulting parts showed higher shrinkage and crystallinity values [15]. Tool life, general surface quality and especially impact on micro feature characteristics such as edge sharpness, hole diameter and thermal performance evaluation of a DLP insert were extensively investigated in [16, 17].

Further extensive work on the influence of part morphology and crystallinity was done by HARRIS et al. In [18] they showed a doubling of the shrinkage of a PA66 molded in a stereolithography (SL) tool compared to the same geometries from an aluminium (AL) tool. The difference in shrinkage behavior was linked primarily to the different processing conditions namely due to the different cooling behavior caused by the different tool material thermal conductivities. Further, a difference in shrinkage using amorphous ABS could not be observed suggesting special caution for shrinkage compensation when semi crystalline or crystalline polymers are used. [19] therefore proposed two approaches to control crystallinity behavior in parts from SL tools. First melt temperature alteration was used to lower the possible melt temperature resulting in a lower crystallinity in PA66 parts from SL tools. Due to the fast cooling in AL tools, the zone in which crystallinity can be influenced is passed to fast, hence melt temperature alteration did not affect crystallinity in parts from AL tools. Second, the use of a nucleating agent provides parts with a consistent crystallinity regardless of the cooling rate resulting in parts with a crystallinity in between the values of parts from SL and AL tools without using a nucleating agent. [20] further showed that the lower thermal conductivity of the polymer tools increases the degree of crystallization of semi-crystalline PA66 injection molded parts, which also increases the shrinkage potential of the injection molded parts. Compared to parts from AL tools, parts from a SL tool developed approx. 30% more crystallinity resulting in a total crystalline difference of approx. 6%. [21] show how the low thermal conductivity of a SL tool can be used to produce fully crystalline PEEK parts at much lower process parameters compared to a conventional steel. It was possible to produce a small number of parts at a

tool temperature of 23 °C and with an injection pressure of 25 bar using a SL tool. According to [21], a tool temperature of approx. 200 °C and an injection pressure of 500 bar would be required using a steel tool to achieve parts with a similar crystalline structure. In addition to that, [22] conclude, that a good heat conducting tool material causes thick boundary layers and small spherulites whereas a poor heat conducting material results in thin boundary layers and large spherulites. Larger spherulites show correlation with increased yield stress of the parts whereas a poor surface quality lowers mechanical properties due to the notch effect.

Besides purely technological analyses, case studies with a focus on economic comparison of the different tool manufacturing routes were also conducted. [23] shows a possible tooling cost reduction of 80%–90% when using polymer based AM to manufacture injection molding tools for two different reference parts within product development phase. Further, a cost effectiveness for the production of up to 3400 units for the smaller reference part and up to 500 units for the bigger reference part were confirmed during a break even analysis. Based on these results, the authors present in [24], how a detailed cost estimation model, considering the AM and injection molding part of the process chain can look like, promoting the idea to use AM as synergistic addition in combination with traditional manufacturing processes. [25] compares the suitability of two different PolyJet materials, "Digital ABS" and "RGD450" for the use of tool production. More than 120 parts of a reference geometry in ABS material were produced successfully. A technological comparison with an aluminum tool as reference showed, that overall form accuracy of the resulting molded part could be reached while required surface roughness could not reach the roughness of parts from the aluminum tool [25]. An economic comparison showed, that for the investigated use case a 10% and 15% saving in overall cost for "Digital ABS" and "RGD450" respectively could be achieved, while lead time could only be reduced by 13% using the "RGD450" tool [25].

The literature shows, that studies focusing on single application fields already investigated printed polymer tools – namely "Digital ABS" material with respect to its suitability as tool material. Further, extensive research to the effect on resulting part material characteristics such as morphology and crystallinity were conducted to help explain the difference in mechanical behavior. However, the increasing number of available materials for polymer additive manufacturing requires a broader study on the suitability of distinct materials for the use of tool production. This paper provides a technological and economic comparison of 10 different additive manufacturing materials with respect to their potential for the use of injection molding tool production, thus serving as an orientation for tool material selection for design engineers.

2   Methodology

2.1   General Trial Procedure

The conducted trials follow the procedure displayed in Fig. 1. After reference geometry and tool design, the tool is tested with different injection molding materials. First, a filling study for the material combination is done to determine the filling parameters resulting in completely filled parts. Filling studies for all tool materials are done

following the same procedure. Starting from initial injection molding parameters, a first shot at 90% of calculated part volume is done. Subsequent parameter adaption is done with respect to observed filling behavior of the part. Thereby final parameters for full volumetric filling of the parts vary between the tool materials. Filling parameters are held constant to produce five volumetric fully filled parts with the same tool. Once five parts with each injection molding material are produced or tool failure occurs, the tool is changed and no further cycles are conducted with this tool material. Technical comparison of the tools after the trials is done by determining the produced number of parts per material combination and via optical inspection of tool wear to assess the possibility to produce further parts. Additionally, weight of the resulting molded parts is compared to determine part quality. Tool manufacturing cost allows for an economic comparison. A conventionally milled steel tool served as a reference.
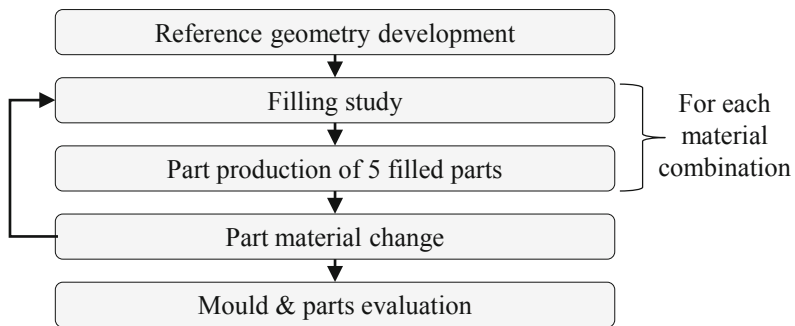

Fig. 1. General trial methodology

2.2 Reference Geometry and Tool Design

Injection molded parts span a broad area of geometric variety starting from parts only a few grams in weight to whole car exterior components or big disposal containers weighing several kilograms. To examine the potential of different tool materials, a preliminary limitation in part size is undertaken in order to keep the tool loads within expected bearable limits. A size limitation to roughly 100 mm in diameter should allow producing parts with every tool material without immediate tool failure. The resulting reference geometry and corresponding tool can be seen in Fig. 2. The geometry covers typical geometric features commonly available in injection molding parts such as holes, ribs and pins in both the part itself and the resulting tool. Tool thickness is 20 mm on the injection and 27 mm on the ejection side to reduce possible clamping of the ejector pins.
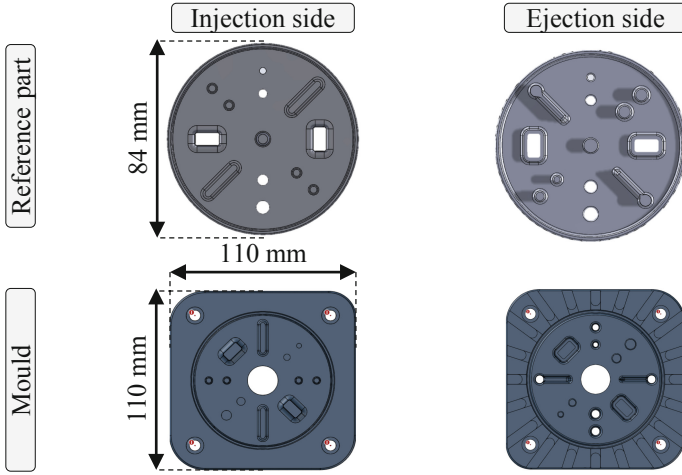
Fig. 2. Reference part and tool geometry

2.3 Tool and Machine Setup

Experience from previous trials as well as [15, 25] state, polymer tools should be incorporated into a standard metal tool frame for both, reducing necessary print volume as well as increasing mechanical stability against thermal and mechanical load during injection molding processes. Figure 3 shows the used tool mounting during the trials. An ejection system was used to remove the parts from the tools without putting additional loads on the tools. Trials were performed using a hydraulic 1600 kN injection molding machine (ENGEL victory 160). Active cooling was not used due to poor thermal conductivity of the printed tools.
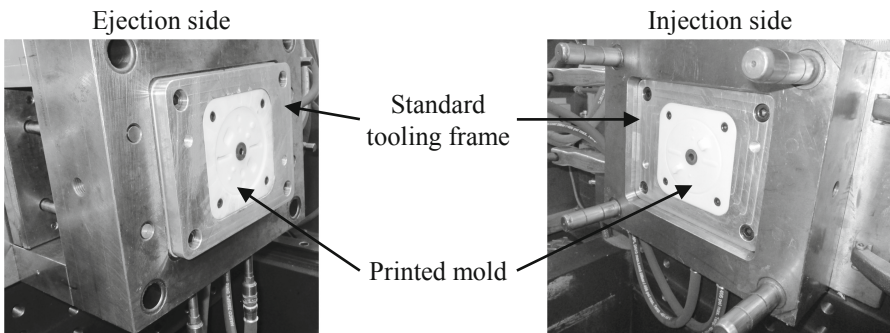

Fig. 3. Tool setup at injection molding machine

2.4   Tested Tool and Part Materials

Overall 10 different additive manufacturing (AM) materials from PolyJet, stereo-olithography, CLIP and selective laser sintering were each tested with three different part materials (PP, PA6, PA6 + GF30%) of increasing difficulty in terms of mechanical and thermal loads on the tools during injection phases. Available material data for AM materials is very scarce and mostly restricted to single values instead of comprehensive material data sets due to the novelty of the materials and the expenditure of required material tests. Further, values for material characteristics are not always measured under same test conditions making comparisons between different AM materials difficult. Nonetheless, material pre-selection needs to be done based on comparable measures. Therefore, the most reliable material characteristics values for the selection of suitable AM materials pose tensile strength (R), elongation at break (ε), heat deflection temperature (HDT) and glass transition temperature (Tg). Thermal conductivity would offer another valuable insight but is not available for most of the materials. Table 1 summarizes the tested AM materials for tool production with the key material characteristics available.

Table 1. Tested tool material characteristics

Material	R [MPa]	ε [%]	HDT@0.45 MPa [°C]	HDT@1.8 MPa [°C]	T_g [°C]
Digital ABS	55–60	25–40	92–95	51–55	47–53
RGD450	40–45	20–35	49–54	45–50	48–52
Accura bluestone	66–68	1.4–2.4	267–284	65	51
Accura SL5530	57–63	3.8–4.4	68	56	82
Accura Xtreme	38–44	14–22	62	54	70–74
High temp	51.1	2	289	130	–
Tough	55.7	24	48.5	45.9	–
PerForm	80	1.2	268	119	81
CE221	79–105	–	231	201	–
PA 3200 GF	47–51	5.5–9	157	96	–

3   Trial Results

Out of the 10 tested AM materials, only three materials (PerForm, PA3200GF, Accura Bluestone) allowed to produce five fully filled parts of each injection molding material. Out of those three only PerForm and PA3200GF were not completely destroyed upon trial ending. While most of the AM tool materials were able to withstand the molding trials with PP part material, PA6 injection molding material posed a challenge mostly due to the higher injection temperature of $\sim$280 °C compared to $\sim$220 °C for PP. Most prominent tool failure mechanism is the breaking of sharp edges or small ribs due to a combination of thermal and mechanical load during injection. Accura Bluestone broke completely into four parts despite not being the most brittle material

according to values for elongation at break, see Table 1. However, it was still possible to manufacture all required parts. Accura SL5530 and Accura Xtreme both performed very poorly breaking either immediately or after very few cycles, allowing to produce no full parts at all or just very few. The PolyJet material "RGD450" allowed to produce PP and PA66 parts with no major damages to the tool. Upon injecting PA66 + GF30% the material deteriorated very quickly allowing to produce only 1 fully filled part. The materials "Digital ABS", "Tough" and "High Temp" all allowed to produce PP parts with no major damages to the tool, but all failed to produce 5 fully filled parts from PA66, where the material "High Temp" deteriorated immediately upon injection PA66 material. Figure 4 summarizes the results.

	# of full parts	PP	PA6	PA6+GF 30%	Tool condition
PolyJet	Digital ABS	5	2		1
	RGD450	5	5	1	0
SLA	Accura Bluestone	5	5	5	0
	Accura SL5530	No full parts			0
	Accura Xtreme	2	2		0
	High Temp	5			0
	Tough	5	2		0
	PerForm	5	5	5	2
CLIP	CE 221	5			0
SLS	PA 3200 GF	5	5	5	2
Milling	Steel reference	5	5	5	3

0: Complete mould failure   2: Low visible mould wear
1: High visible wear, mould failure imminent   3: No visible mould wear

Fig. 4. Trial results – number of fully filled parts and tool condition after trials

Looking at the average weights of the parts produced in Table 2, the performance of the different AM materials with respect to filling behavior can be compared. It becomes evident, that deviation of part weights are smallest for PerForm material for all molded materials while highest deviations can be attributed to PA 3200 GF tool compared to parts from the steel reference tool. The lowest deviation of about 0,7% was achieved when molding PP in a PerForm tool. The highest deviation occurred when molding an PA66 part in a PA 3200 GF tool.

Taking additionally tool surface roughness into account, one explanation for the different filling levels can be given by a significantly weaker effect of holding pressure using a PA 3200 GF tool compared to a PerForm tool due to a poorer surface roughness and thus worse flowing properties of the liquid polymer in the tool. The higher surface roughness effectively hinders the molten material to flow resulting in less dense parts. However, it has to be noted, that different injection molding parameters were used for

Table 2. Average weight of the parts produced

Material	PP		PA6		PA6 + GF30%	
	w [g]	dev.[%]	w [g]	dev.[%]	w [g]	dev.[%]
Digital ABS	13,1	−3,7	18,2	−4,7	–	–
RGD450	12,14	−10,7	16,92	−11,4	18,8	−10,0
Accura bluestone	13,5	−0,7	18	−5,8	20,6	−1,4
Accura SL5530	–	–	–	–	–	–
Accura Xtreme	14,4	5,9	17	−11,0	–	–
High temp	14,1	3,7	–	–	–	–
Tough	14,1	3,7	17,04	−10,8	–	–
PerForm	13,7	0,7	18,16	−4,9	20,6	−1,4
CE221	14,1	3,7	–	–	–	–
PA 3200 GF	12,5	−8,1	16,5	−13,6	19,8	−5,3
Steel reference	13,6	0,0	19,1	0,0	20,9	0,0

the tested materials as finding the optimal parameter set was not an objective. Hence, influence of these variations needs to be considered before deriving definitive conclusions.

A tool manufacturing cost comparison offers an economic view on the potential of different materials for tool manufacturing. As costs for different manufacturing technologies vary greatly between companies depending on many factors like machine availability or economies of scale, a relative cost comparison using the milled steel tool as a reference is done. Prices for printed tools are obtained from different on demand manufacturing suppliers and averaged to get a more objective view of the market prices. Except Accura Bluestone material, all printed tools offered a reduction in manufacturing cost. From a perspective of tool manufacturing cost, PA 3200 GF offers the highest economic potential with a cost reduction of 84.2% compared to a steel tool. The PerForm tool offered a 23.9% cost reduction. Figure 5 displays the summarized results.

Relative tool manufacturing cost [%]
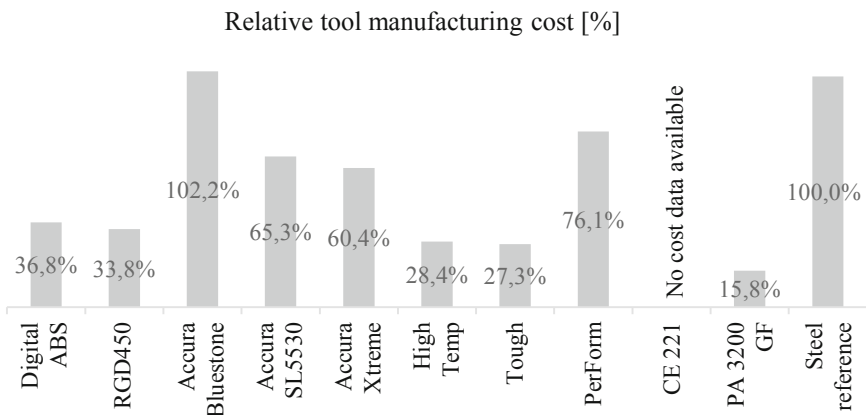
Fig. 5. Tool production cost comparison

4   Conclusions

This comparative study provided an overview of the technological and economic potential of 10 different AM materials for the use as injection molding tools. Trials with three different injection molding materials were performed and the resulting part weights and tool wear were evaluated following a standardized methodology.

From a technological point of view, only PerForm and PA 3200 GF are suited to manufacture all three tested materials without suffering from complete tool failure suggesting a higher potential for tool manufacturing. Accura SL5530 and Accura Xtreme were the only AM materials not capable of manufacturing one set of five parts of at least one part material suggesting a poor suitability for the tool manufacturing. For lower melting polymers like PP in this study, a variety of potential AM materials could be used. Comparing the results with the material characteristics from Table 1 the results of the trials can only be explained partially. The poorest performers, namely Accura SL5530 and Accura Xtreme both have a comparably low HDT while at the same time having a low elongation at break, indicating that a combination of low values of those two material characteristics result in poor behavior as injection molding tool. Digital ABS, RGD450 and Tough all also have low HDTs but at the same time, significantly higher values for elongation at break suggesting a more ductile behavior and therefore a possibly higher resistance against breaking upon deformation. Accura Bluestone, Perform, High Temp and CE221 show the highest HDT with at the same time the lowest values for elongation at break suggesting a very brittle material behavior. While indeed, a brittle behavior for Accura Bluestone and Tough could be observed during the trials, failure mechanism for CE221 was a complete malfunction of the mechanical behavior during deforming of PA66. It has to be noted, that the tool from CE221 had to be printed with an inner lattice structure as it was not possible to print the tool as a solid body due to limitations within the manufacturability of CLIP technology. Therefore, it was significantly more likely to fail during trials. PerForm however suffered mild cracks in the surface of the tool but was unaffected by the trials other than that. Surprisingly the PA 3200 GF tool generated good results in terms of number of full parts produced. As material characteristics for this material are in the middle of the extremes, a concrete explanation solely based on the available material characteristics for the performance cannot be given.

From an economic point of view, PA 3200 GF offers the highest cost savings in tool manufacturing. While cost savings seem significant, increased cycle times and decreased tool life needs to be considered to get a comprehensive view of the cost savings potential. Hence, a decision for a concrete material will always be subject to a trade-off between cost, lead time, required part quantity and part finish.

This study offers a first glance at the potential for different AM materials for the use as tool material for injection molding. PerFrom and PA 3200 GF offer the highest technological potential even for high melting polymer materials and therefore should be further investigated with priority. Digital ABS, RGD 450, Tough and Accura Bluestone also offer technological benefits and could also be investigated with a secondary priority. Accura SL5530, Accura Xtreme, High Temp and CE221 should not

further be investigated as they offer little to no potential from a technological point of view. Considering the economic evaluation for tool manufacturing as of today, PA 3200 GF offers the highest potential. However, it should be considered, that market prices for AM materials are likely to decline with increasing material development and available supply. Further, achievable surface roughness for PA 3200 GF poses a possible limitation. In [26] a method to reduce surface roughness of SLS parts is introduced. Here, the surface roughness of sintered PA 12 could be effectively reduced to 10 µm Rz by exposing specimens to trifluoroacetic acid for 120 s lifting it on the same level as PerForm material. However, industrial application needs to be verified due to handling issues with the aggressive acid.

Further trials with the proposed AM materials should include a systematic investigation to fathom the achievable geometric limits of possible parts in terms of size and level of detail. It is also of essential importance to better understand the material behavior of printed tools. As this study shows, available AM material data is neither complete, nor coherent, as the observed tool lives during trials could not clearly be attributed to specific material characteristics. Therefore, a specific material model that can be used to simulate the effects of thermal and mechanical loads during injection molding would be extremely helpful to predict tool life. A study on the influence of tool design changes on tool life and part filling behavior is also required. Finally, a comprehensive cost calculation model to integrate tool manufacturing cost as well as occurring cost during injection molding itself, taking into account tool life is essential to determine economic potential of any given AM material for injection molding tool.

5 Acknowledgements

References

1. Kampker, A., Burggräf, P., Wesch-Potente, C., Petersohn, G., Krunke, M.: Life cycle oriented evaluation of flexibility in investment decisions for automated assembly systems. CIRP J. Manuf. Sci. Technol. **6**(4), 274–280 (2013)
2. Kampker, A., Burggräf, P., Deutskens, C., Maue, A., Förstmann, R.: Integrated product and process development: modular production architectures based on process requirements. Procedia CIRP **20**, 109–114 (2014)
3. Altan, T., Lilly, B., Yen, Y.C.: Manufacturing of dies and molds. CIRP Ann. **50**(2), 404–422 (2001)
4. Levy, G.N., Schindel, R., Kruth, J.P.: Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Ann. **52**(2), 589–609 (2003)
5. Rahmati, S.: Direct rapid tooling. Compr. Mat. Process., 303–344 (2014). Elsevier
6. Kampker, A., Förstmann, R., Kawollek, S., Bride, B.: Additive tooling für kunststoffbasierte urformverfahren. Lightweight Des. **9**(2), 38–43 (2016)

7. Segal, J.I., Campbell, R.I.: A review of research into the effects of rapid tooling on part properties. Rapid Prototyp. J. **7**(2), 90–99 (2001)

8. Martinho, P.G., Bártolo, P.J., Pouzada, A.S.: Hybrid moulds: effect of the moulding blocks on the morphology and dimensional properties. Rapid Prototyp. J. **15**(1), 71–82 (2009)

9. Chua, C.K., Hong, K.H., Ho, S.L.: Rapid tooling technology. Part 1. a comparative study. Int. J. Adv. Manuf. Technol. **15**(8), 604–608 (1999)

10. Rosochowski, A., Matuszak, A.: Rapid tooling: the state of the art. J. Mat. Process. Technol. **106**(1), 191–198 (2000)

11. Oroszlany, Á., Nagy, P., Kovács, J.G.: Injection molding of degradable interference screws into polymeric mold. MSF **659**, 73–77 (2010)

12. Noble, J., Walczak, K., Dornfeld, D.: Rapid tooling injection molded prototypes: a case study in artificial photosynthesis technology. Procedia CIRP **14**, 251–256 (2014)

13. Volpato, N., Solis, D.M., Costa, C.A.: An analysis of Digital ABS as a rapid tooling material for polymer injection moulding. IJMPT **52**(1/2), 3 (2016)

14. Tábi, T., et al.: Comparison of thermal, mechanical and thermomechanical properties of poly (lactic acid) injection-molded into epoxy-based Rapid Prototyped (PolyJet) and conventional steel mold. J. Therm. Anal. Calorim. **123**(1), 349–361 (2016)

15. Mendible, G.A., Rulander, J.A., Johnston, S.P.: Comparative study of rapid and conventional tooling for plastics injection molding. Rapid Prototyp. J. **23**(2), 344–352 (2017)

16. Mischkot, M., et al.: performance simulation and verification of vat photopolymerization based, additively manufactured injection molding inserts with micro-features. In: Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications – AMPA 2017, 162–168 (2018)

17. Mischkot, M., et al.: Dimensional accuracy of Acrylonitrile Butadiene Styrene injection molded parts produced in a pilot production with an additively manufactured insert. In: 33rd International Conference of The Polymer Processing Society (PPS-33) (2018)

18. Harris, R., Newlyn, H., Hague, R., Dickens, P.: Part shrinkage anomilies from stereolithography injection mould tooling. Int. J. Mach. Tools Manuf **43**(9), 879–887 (2003)

19. Harris, R.A., Hague, R.J.M., Dickens, P.M.: Crystallinity control in parts produced from stereolithography injection mould tooling. Proc. Inst. Mech. Eng., Part L: J. Mat.: Des. Appl. **217**(4), 269–276 (2003)

20. Harris, R.A., Hague, R., Dickens, P.M.: The structure of parts produced by stereolithography injection mould tools and the effect on part shrinkage. Int. J. Mach. Tools Manuf **44**(1), 59–64 (2004)

21. Harris, R.A., Hague, R.J.M., Dickens, P.M.: Thermal conditions in stereolithography injection mould tooling and their use for polyether-ether-ketone moulding. Int. J. Prod. Res. **42**(1), 119–129 (2004)

22. Michaeli, W., Lindner, F.: Influence of mould materials on the morphological and mechanical properties of injection-moulded prototypes. Macromol. Mat. Eng. **286**(4), 232–236 (2001)

23. Charalambis, A., et al.: Economic trade-offs of additive manufacturing integration in injection moulding process chain

24. Charalambis, A., Kerbache, L., Tosello, G., Pedersen, D., Mischkot, M.: Economic analysis of additive manufacturing integration in injection molding process chain. In: Proceedings on 7th International Conference on Industrial Engineering and Systems Management (2017)

25. Kampker, A., Triebs, J., Kawollek, S., Ayvaz, P.: Direct polymer additive tooling – verwendung von polymerwerkzeugen für den einsatz im kleinserien spritzguss. In: Kynast, M., Eichmann, M., Witt, G. (eds.): Rapid.Tech + FabCon 3.D – International Trade Show & Conference for Additive Manufacturing 2018, pp. 45–62. Hanser, München (2018)
26. Wiedau,, L.C., Meyer, L., Wegner, A., Witt, G.: Chemisches nachbehandeln von laser-sinter-proben – einflussuntersuchung von verschiedenen säuren auf die oberflächentopologie. In: Kynast, M., Eichmann, M. and Witt, G. (eds.) Rapid. Tech + FabCon 3.D – International Trade Show & Conference for Additive Manufacturing 2018, pp 267–282. Hanser, München (2018)