Journal of
Composites Science

Review

Variable Shape Tooling for Composite Manufacturing: A Systematic Review

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Abstract: The choice of material, manufacturing process, and molding tool significantly affects the quality, environmental impact, and cost efficiency of composite components. Producing one-piece hollow profiles with smooth inner surfaces and undercuts presents major challenges for conventional mold concepts. There is yet no thorough review of shape-variable mandrels in composite manufacturing to be found in the literature. This paper provides an overview of research on shape memory polymers and other shape-variable materials used in tooling applications for composite manufacturing. This work covers shape memory, heat shrink, and other deformable tooling concepts that enable the production of one-piece Type V pressure vessels, air intake ducts, or curved struts and tubes. A systematic literature review in combination with a state-of-the-art open-source active learning tool *ASReview* is conducted. Fifteen relevant studies were identified. Research on shape-variable tooling is mainly conducted by three research groups in the USA and the PRC. The tooling is mostly made of unreinforced thermosets, especially styrene-based ones. Thermoplastic resins are less common, and reinforcements limit the usable elongation in the temporary shape. The shape variability is either a shape memory and/or a softening process, which, in all studies, is activated by heating. Release agents are widely used to ease demolding. No ecological or economical assessment of the manufacturing methods was conducted in the reviewed studies. Three fields for further research that could be identified are as follows: (1) thorough ecological end economical assessment of shape-variable mandrels in comparison with conventional tooling; (2) thermoplastic shape memory polymer mandrels; and (3) further investigation of simulation capabilities for shape memory mandrels.

Keywords: tooling; shape memory polymer; automated fiber placement (AFP); winding; braiding; liquid composite molding; hollow profile; fiber composite

Citation: Neumann, F. Variable Shape Tooling for Composite Manufacturing: A Systematic Review. *J. Compos. Sci.* **2024**, *8*, 131. https://doi.org/10.3390/jcs8040131

Academic Editor: Francesco Tornabene

Received: 16 February 2024
Revised: 20 March 2024
Accepted: 28 March 2024
Published: 3 April 2024

1. Introduction

This paper is based on a proceeding presented at the SAMPE Europe Conference 2023 [1]. Fiber-reinforced polymer (FRP) composites are one of the dominant materials in aerospace applications. They offer good fatigue behavior, excellent material properties, and the possibility to tailor them by varying their fiber angles. Therefore, the percentage of FRP in the structural mass of the current civil aircraft like Airbus A350 or Boeing 787 is at about 50%. In General Aviation and in Unmanned Aerial Vehicles, FRP accounts for more than 90% of the structural mass [2]. Furthermore, there is a strongly growing market forecasted for Urban Air Mobility, expecting 160,000 passenger drones until 2050, even if there are some uncertainties regarding the certification and performance of those aircraft [3,4]. Furthermore, the production of pressure vessels for hydrogen-powered cars and airplanes is expected to grow strongly over the next decade [5]. To cover the demand of FRP parts for those applications, highly automated manufacturing processes will be needed. Likewise, producing one-piece hollow profiles with smooth inner surfaces and undercuts (e.g., complex struts, air inlet ducts, or Type V pressure vessels) still presents major challenges for conventional mold concepts. Feasible production methods for the automated manufacturing of hollow profiles with undercuts are filament or towpreg winding, automated fiber placement (AFP), and braiding [6]. Mandrels for these processes can be classified into categories as shown in Table 1.

Table 1. Classification of cores for hollow composite profiles [7].

Remaining Cores	Cores with component function Cores without component function
Removable Cores	Directly reusable cores Indirectly reusable cores Lost cores

Removable cores can be further classified. Multi-piece rigid cores are expensive to manufacture and time consuming to geometrically assemble and disassemble with a high accuracy [8]. Low-melt metal alloy cores offer a high accuracy in terms of geometry, but they have to be removed at higher temperatures (above the alloy's melting point). Thus, they are high in energy consumption for forming, demolding, and reforming [9]. Wax cores are similar to metal alloy cores, but less expensive, and they can be melted at lower temperatures. On the other hand, they are susceptible to damage during handling and not as rigid as metal alloy cores. Water- or solvent-soluble cores can be made from salt, plaster, or polymers but removing them is time consuming and associated with dirt. Also reusing the material requires elaborate preparation [10,11]. Expandable cores made of rubber such as silicone are limited in their ability to be demolded from undercuts and are too soft to be used as a mandrel for fiber lay-up and debulking [12]. First, papers covering cores for the automated production of hollow composite profiles using removable mandrels were published in the late 1990s. Lehmann et al. [13] investigated bladder molding and the flow characteristics within the Resin Transfer Molding (RTM) process. Inflatable cores such as silicone or foil hose bladders are easily removable from undercuts but offer no possibility to be used for preforming. This paper focuses on removable and reusable cores, which can be used as a mandrel for automated production processes of hollow composite profiles with undercuts. For this application, it is necessary that the mandrel is rigid for preforming at room temperature, but demolding must be possible after cure. In this sense, a mechanism is required to either change the shape of the mandrel or manipulate its material properties in a way that the resolution of undercuts becomes possible. Polymers, especially shape memory polymers (SMP), could be suitable materials for such applications. This makes it possible to produce one-piece Type V pressure vessels, for example, for hydrogen-powered cars and aircraft, without soluble cores. The pressure vessel could be wound onto a polymer mandrel, which can be easily removed after curing by heating. S-shaped air intake ducts could be produced by AFP without the need for expensive multi-piece rigid tooling. Blow-molded mandrels can even decouple the rate of part production from the number of mandrels in stock. This is made possible by the ability to produce multiple positive mandrels at high rates from a single negative mold in the blow-molding machine. In addition, complex curved struts and tubes for trusses or fluid lines could be produced either at high rates on blow-molded mandrels or with a tailored shape for each part on the same mandrel using a SMP mandrel. To address the production conditions of these case studies, this study defines ten research questions covering the FRP production process with shape-variable tooling, which are shown in Table 2. The first three research questions cover the material and production of the mandrel. This includes investigating the mandrel material, possible fillers or reinforcements, and its production method. Research questions four to six investigate the processes of performing, curing, and demolding the composite part. Firstly, the manufacturing method and the manufactured part are investigated. Secondly, the method of activating shape variability is examined. Finally, the use of release agents to facilitate demolding is examined. Furthermore, research questions seven to nine focus on the simulation of the shape variability process, if the mandrel can be reused, and if the economic and ecological advantages were examined. In Section 1.1, a short overview of the classification of SMP is given, followed by an introduction of the systematic literature review (SLR) in Section 1.2. In Section 2, the research methodology of the SLR on "Variable Shape Tooling for Composite Manufacturing" is described. The results are elaborated in Section 3 and discussed in Section 4. Finally, Section 5 concludes this paper and provides an overview of further research topics synthesized from the SLR.

Table 2. Research questions.

No.	Research Question
RQ1	Which polymer material is used?
RQ2	Is the mandrel of the neat material or is a filler or reinforcement used?
RQ3	How is the mandrel manufactured?
RQ4	Which composite manufacturing method is used and what is manufactured?
RQ5	How is the shape variability activated?
RQ6	Is any release agent used for demolding?
RQ7	Is the shape variability simulated?
RQ8	Is the mold reused? How many times can it be reused?
RQ9	Is an economical or ecological assessment conducted?

1.1. Classification of Shape Memory Polymers

SMPs can be classified in different manners: by overall type of the polymer, by the base polymer, or by the activation method [14]. The overall SMP types are (1) partially cured thermosets, (2) fully cured thermoset systems, and (3) thermoplastics [15]. Additionally, there have been SMPs synthesized which are blends of at least two of the above-mentioned overall types [16]. Disadvantages of the above-mentioned categories are that partially cured thermosets continue to cure during their use as SMPs, which results in changes in their material property with every cycle. Thermoplastic SMPs show creeping behavior, which means that they forget their memory shape over time [15]. Therefore, the main research effort is focused on fully cured thermoset systems. In the literature, the already investigated SMP base polymers are mainly polyurethane-based SMPs [17,18], styrene-based SMPs [19,20], epoxy-based SMPs [21,22], cyanate ester-based SMPs [23,24], and polyamide-based SMPs [25]. In the literature, the investigated activation methods cover those which are temperature induced [19], electricity induced [17], light induced [26], microwave induced [27], magnetic induced [28], or water induced [29].

1.2. Systematic Literature Review (SLR)

Scientific databases offer access to thousands of journals and millions of papers. For example, "ScienceDirect" grants access to 4770 journals, with more than 19 million scientific papers [30]. Traditional reviews using snowballing from one or more identified pieces of literature are not able to cover all relevant published papers. One technique to face this hurdle is the Systematic Literature Review. The SLR originates in medical research where a huge number of studies are to be reviewed to observe connections in diseases, symptoms, and therapies. One of the main publications about SLR is "Cochrane handbook for systematic reviews of interventions" [31]. This handbook was adopted by Kitchenham (2004) [32] to meet the requirements of systematic reviews in software engineering. This paper follows the review process steps adapted from the prior mentioned study and the structure of van Dinter et al. (2021) [33] and Jilke et al. [34]. Figure 1 illustrates these process steps. The SLR starts by defining a review protocol that outlines the research questions to be answered by the review, see Section 2.1. Then, a search strategy is developed defining the scope, method, search string, and selection criteria, see Section 2.2. The study selection is supported by a state-of-the-art open-source active learning tool *ASReview* to speed up the filtering process to identify all relevant studies [35]. According to van Dinter et al. (2021) [33], this is the most effective and common method to automate the systematic literature review process.

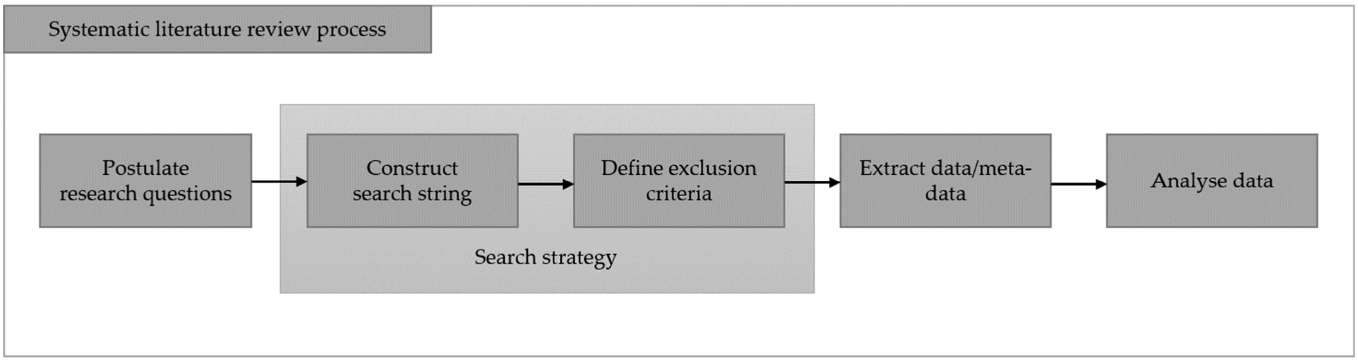

Figure 1. Schematic review process.

2. Methods

In a preliminary search for secondary literature regarding variable shape tooling for composite manufacturing, no up-to-date review could be identified. Lehmann et al. (1998) does not cover shape-variable mandrels at all, which seems logical since research on these materials had just began by that time [13]. Gibbons et al. (2009) review the "State of the Art in Low-cost, Rapid Composite Forming Tooling Technologies" but do not cover mandrels for hollow composite profiles [36]. Leng et al. (2011) review "Shape-memory polymers and their composites: Stimulus methods and applications" but do not state details on research regarding SMP mandrels [37]. Liu et al. (2014) reviewed "shape memory polymers and their composites in aerospace applications" but are focused on components made of SMP or SMP composites and do not review tooling applications [38]. Hager et al. (2015) review SMP developments but not their application [39]. Li et al. (2019) review the "Progress of shape memory polymers and their composites in aerospace applications" without mentioning tooling applications [40]. Li et al. (2022) mention SMP as a tooling material but do not provide a thorough review of research studies in this field [2]. Zhao et al. (2023) review "Mechanical behaviors and applications of shape memory polymer and its composites", only covering tooling applications in the same extent as Li et al. (2022) [41]. Since no thorough review of shape-variable mandrels in composite manufacturing was found in literature and 23% of all SLR studies are outdated within two years [33], there is a research gap this study fills. Therefore, an SLR is conducted following the research protocol shown in Figure 1.

2.1. Research Questions

The developed research questions (RQ) shown in Table 2 aim to provide answers to the complete process chain of manufacturing of shape-variable mandrels. Material and production of the mandrel is covered by RQ1–RQ3. Preforming, curing, and demolding of the composite part is investigated by RQ4–RQ6. Finally, it is investigated if the shape variability process is covered by a simulation (RQ7), if the mandrel can be reused (RQ8), and if the economic and ecological advantages were examined (RQ9).

2.2. Search Strategy

The aim of this SLR is to find as many relevant primary studies on shape-variable tooling applications in composite manufacturing as possible (high recall) but neglecting irrelevant studies (high precision). Therefore, a suitable search strategy is developed in the following sub-sections.

2.2.1. Search Scope

The scope of this SLR can be split in two categories: publication period and publication venue. The considered publication period is from January 2000 to May 2023. The lower boundary was set by Lehmann and Michaeli (1998) [13] without mentioning SMP mandrels in their review, and Lendlein and Kelch (2002) [42] were the first to review the research on

SMP. The search for this paper was conducted in May 2023. Later publications could not be considered. This paper covers the following publication venues: Scopus, ScienceDirect, Web of Science, IEEEXplore Digital Library, Wiley Online Library, and Taylor and Francis.

2.2.2. Search Method

In this SLR, an automated literature search was used. This means that, for each aforementioned research database, an automated search based on a search string was conducted. Furthermore, the dissertation by Miadowitz (2019) [43], which is not accessible online, was added to the scope. Additionally, the search was supported with a manual snowballing approach. After the identification of relevant studies according to Section 2.2.4, the references and citations of these papers were checked for further relevant studies not already in scope.

2.2.3. Search String

A search string with Boolean operators was used to find all articles regarding shape-variable tooling for the production of FRP. The string was iteratively refined to improve recall and precision using several pilot searches. Due to *ScienceDirect*, the string had to be limited to eight Boolean operators. In this way, the derived search string is as follows:

("shape memory polymer" OR "heat shrinkable" OR "deformable") AND ("mold" OR "mandrel")
AND ("fiber") AND ("composites") AND ("manufacturing" OR "winding")

Some databases required a different syntax, so the string was adapted to the requirements of each database. The keywords and their logical connection were always maintained.

2.2.4. Study Selection Criteria

To identify the relevant studies, exclusion criteria (EC) were introduced, which are shown in Table 3. As shown in Table 4, the defined search string has an extensive recall. The most studies were found in the ScienceDirect database, accounting for 86% of all results. Since EC4–EC6 are not content-related, they were directly applied to the results from the automated search. The content-related exclusion criteria, EC1–EC3, were applied to the prefiltered studies using open-source *ASReview*, which is a state-of-the-art active learning tool to label and rank studies based on their title and abstract. The algorithm ranks the studies based on previous knowledge (labeled studies), recommends the next most likely relevant study and regenerates the ranking after every new labeled study. The stop criterion was defined as the point when *ASReview* recommended 100 studies in a row that had to be labeled as irrelevant. As shown in Table 4, 10.186 studies are found with the automated search. The titles and abstracts of 3.217 papers are then collected and fed into the *ASReview* tool separated by their publication venue. After applying EC1–EC3 using *ASReview*, probably 58 relevant studies were identified after labeling 760 titles and abstracts.

Table 3. Study exclusion criteria.

No.	Exclusion Criteria (EC)
EC1	Full text unavailable
EC2	Duplicate publication
EC3	Does not relate to shape-variable tooling/mandrel
EC4	Study not written in English or German
EC5	Study published before 2000
EC6	Study is not a primary research article or conference proceeding

The 58 studies that were identified within their publication venues were then merged and reviewed again in terms of EC1–EC3. Next, the full texts of the 30 remaining studies were obtained, and the exclusion criteria were applied to the full papers. Finally, 15 papers remained as relevant studies for the SLR.

Table 4. Search results and study selection.

Source	After Automated Search	After Exclusion Criteria (EC4–EC6)	After *ASReview* (EC1–EC3)
Scopus	878	497	29 (195 labeled)
ScienceDirect	8769	2357	9 (313 labeled)
Web of Science	40	36	3 (36 labeled)
IEEEXplore	5	0	0
Wiley Online Library	392	239	7 (128 labeled)
Taylor and Francis	102	88	10 (88 labeled)
Total	10.186	3217	58 (760 labeled)

2.3. Data Extraction and Analysis

After filtering and quality assessing the aforementioned full-text studies, a data extraction form based on the research questions in Table 2 was collated. Finally, the metadata such as title, abstract, year, author(s), and the relevant content to answer the research questions were extracted. The collected data are analyzed and interpreted in Section 3.

3. Results

The aim of this section is to provide insights into the main statistics derived from the 15 relevant primary studies identified in Section 2. Furthermore, the extracted data are analyzed and interpreted to answer the research questions.

3.1. Main Statistics

The 15 relevant studies regarding variable shape tooling for composite manufacturing date from 2004 to 2021. The year-wise distribution of the relevant publications is shown in Figure 2. There are two identifiable research periods. The first period ranges from 2004 to 2006 with a peak in 2005. All studies in this period were published by researchers from the Cornerstone Research Group Inc., an aerospace and defense firm based in Miamisburg, Ohio, USA [15,19,23,44], with [45] from the second period connected to it. The second period ranges from 2014 until the present day. When evaluating the authors who published relevant studies as main authors, as shown in Figure 3, there is only Haiyang Du standing out. Therefore, Figure 4 evaluates the authors who published relevant studies including co-authorship. In this way, it becomes evident that the relevant studies are highly interconnected with the co-authors. The three studies with the most authorships did not publish any of the relevant studies as the main author. By investigating these interconnected studies, two research groups can be identified who contributed 60% of the relevant studies. The research group accounting for 40% of the relevant studies conducted their research at the Harbin Institute of Technology, Harbin, PRC. Most relevant authors are Haiyang Du, Liwu Liu, Yanju Liu, and Jinsong Leng. The other research group accounting for 20% of the relevant studies conducted their research at the Beihang University, Beijing, PRC. Most relevant authors are Xishuang Jing, Chengyang Zhang, Fenghua Zhang, and Siyu Chen. These connections can also be made evident through the publication venue, clearly shown in Figure 5. The research group from the Harbin Institute of Technology published in “Composite Structures”, “Composites: Part A&B”, and “Polymer Testing”. The research group from the Beihang University published in “Aerospace”, “AIAM”, and “Journal of Physics”. Both research groups show enclosed publishing venues. In contrast, the USA research group published in three different venues, which are not interconnected with the authors. All relevant studies but one were published by three research groups in the PRC and the USA. The only relevant European study is the dissertation of Thomas Miadowitz, which is not accessible online, and is only available in German.

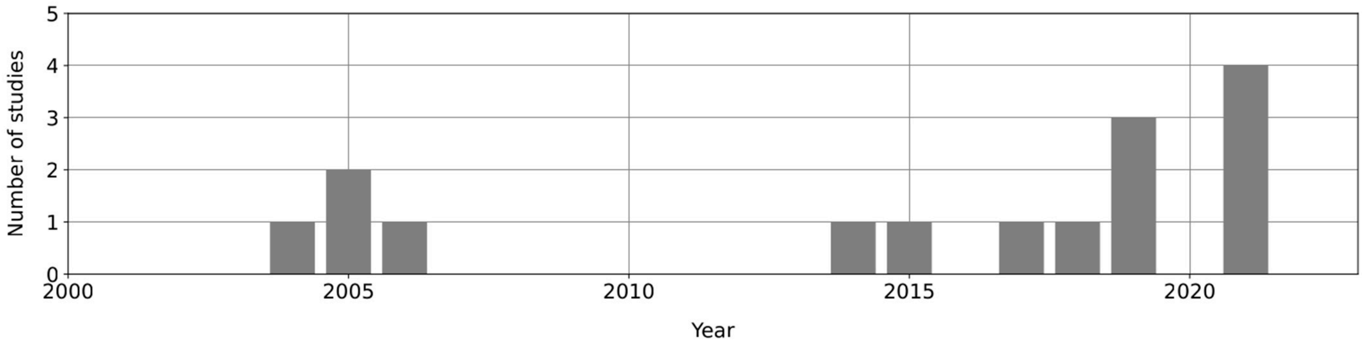

Figure 2. Year-wise distribution of relevant studies.

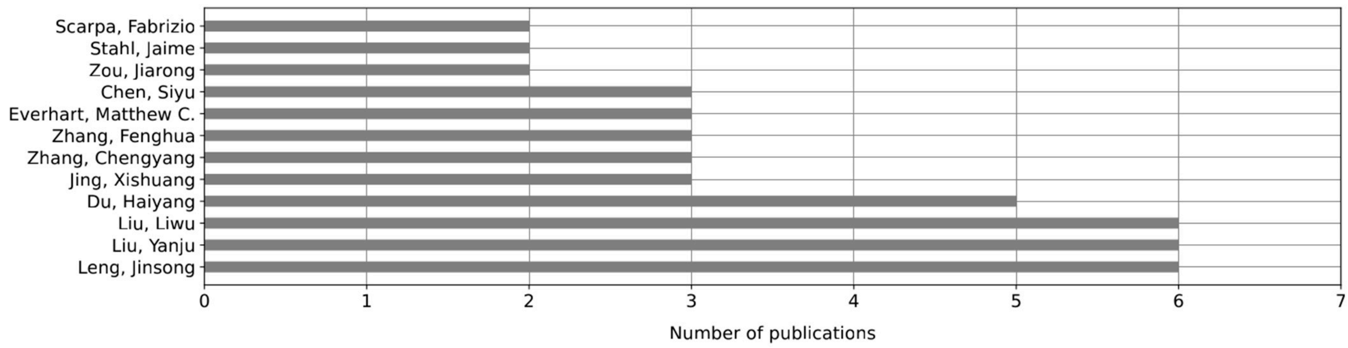

Figure 3. Authors who published relevant studies as main authors.

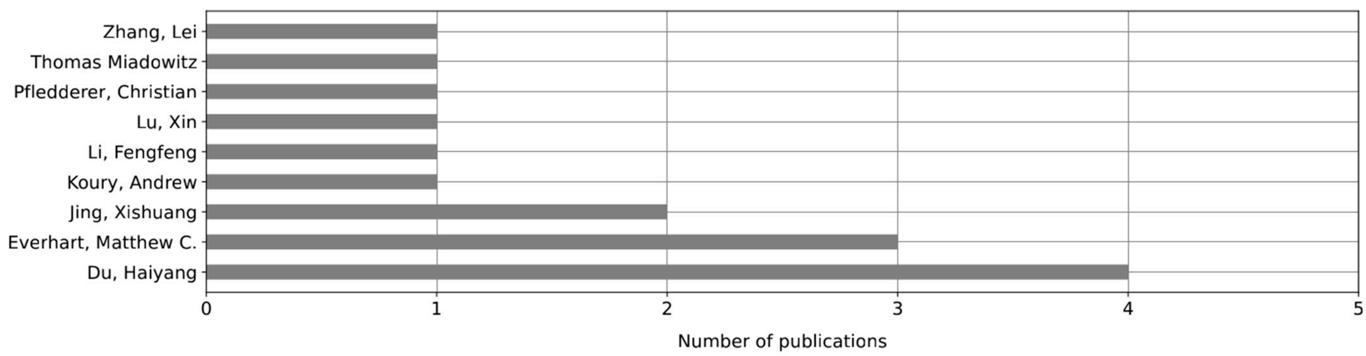

Figure 4. Authors who published more than one relevant study (including co-authorship).

3.2. Results: Research Questions

In this section, the research questions will be answered using the extracted data from the relevant primary studies. For ease of access, each finding is illustrated by a sunburst diagram. In the center of each diagram, the topic of the corresponding research question is shown on a white background, such as the polymer material used in Figure 6. The inner colored ring shows the general answer to the research question. The size of the ring sections corresponds to the percentage of relevant papers with the property shown. The actual percentage or absolute number of relevant studies is not shown in the figure but can be found in the explanatory text. For example, Figure 6 shows that about three quarters of the relevant studies focus on thermoset polymers. In the accompanying text, this is further specified as 73% or 11/15 studies. Each other colored ring shows more specific information about the inner rings. Figure 6 shows that, of the eleven studies on thermoset polymers, eight focus on styrene-based polymers, corresponding to a ring section that covers almost three quarters of the thermoset section.

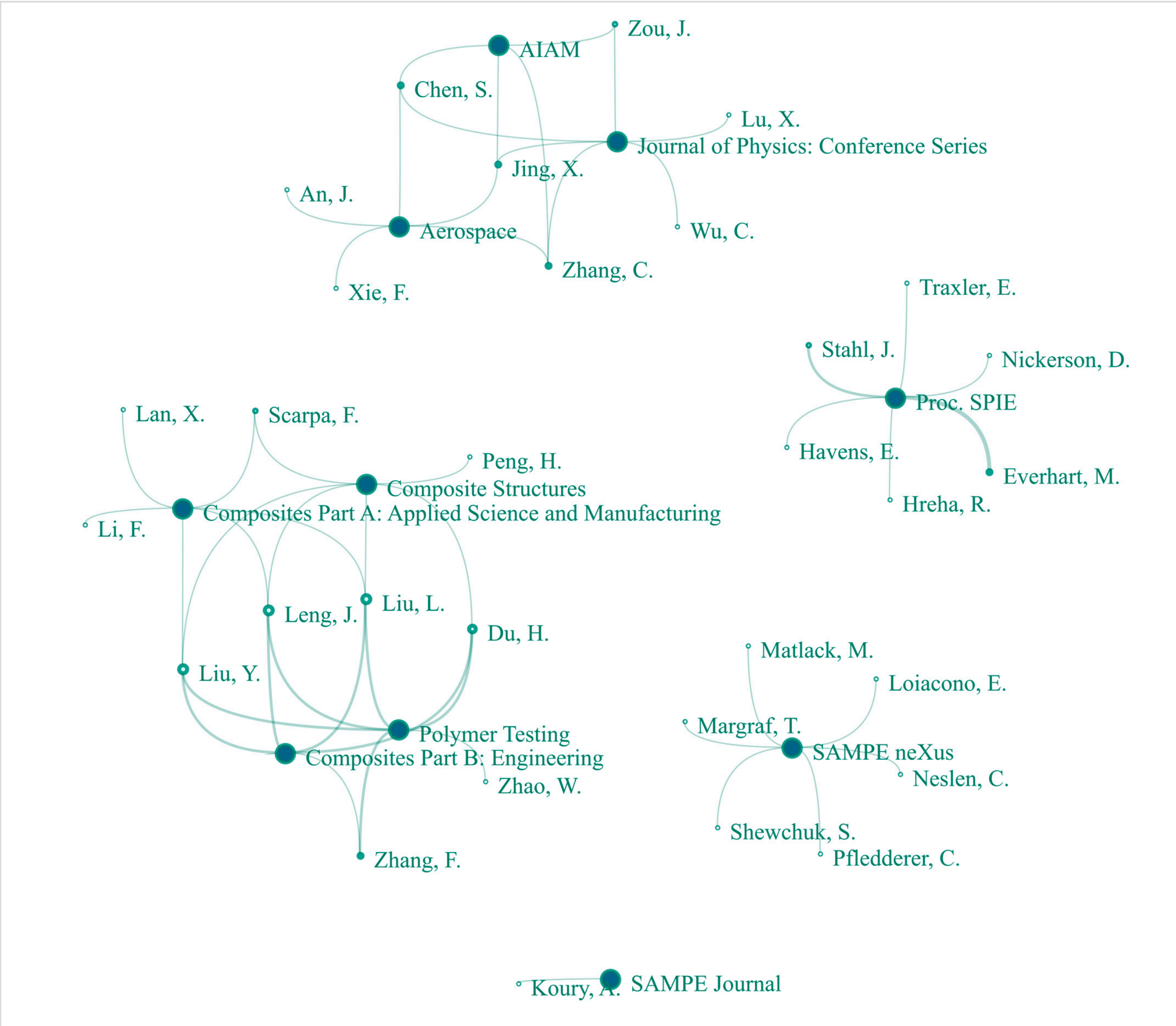

Figure 5. Interconnections between the authors through publication venues.

3.2.1. Polymer Mandrel Material (RQ1)

In 73% (11/15) of the studies, a thermoset is used. In eight studies (53%), a styrene-based polymer is used [14,15,19,20,44,46–48]. In one study (7%), an epoxy-based polymer is investigated [49]. One study (7%) investigates a cyanate-ester-based SMP [23]. Two studies (13%) focus on blends of thermoplastic resins based on PMMA with an epoxy-based thermoset [16,50]. Two studies (13%) investigate thermoplastics: PMMA (7%) [51] and PP, PA6, and PBT (7%) [43]. These findings are shown in Figure 6.

3.2.2. Reinforcements and Fillers (RQ2)

Reinforcing the neat polymer raises the mechanical properties of the mandrel but constricts the possible deflection when programming the temporary shape of the SMP [23]. Therefore, most of the research (53%) was conducted with neat polymer mandrels to allow for elongations of up to 200% in the temporary shape [46]. Everhart et al. (2006) [23] and Koury (2005) [44] (13%) used high-strain fiber reinforcement not specified elsewhere, which allow for elongations of up to 150%. Jing et al. (2021) [50,51] and Lu et al. [16] (20%) used carbon fiber fabric reinforcement. Since they only utilized the softening-by-heating effect, no elongation of the polymer was required. Li et al. (2019) [49] (7%) used unidirectional carbon fibers as reinforcement. In this way, the radial elongation of the mandrel was not hindered in the temporary shape with enhanced diameter. Miadowitz (2019) (7%)

used neat PP, PP_5TC, PP_10TC, PP_20TC, PP_10GF, PP_20GP, PA6_15GF, and PBT_15GF. In these, the first letters identify the polymer, the numbers identify the percentage of filler, and the last letters identify the filler: TC—talcum; GF—chopped glass fiber; and GP—graphite. After a material comparison, unfilled PP as reference and PP_20TC were further investigated [43]. These findings are shown in Figure 7.

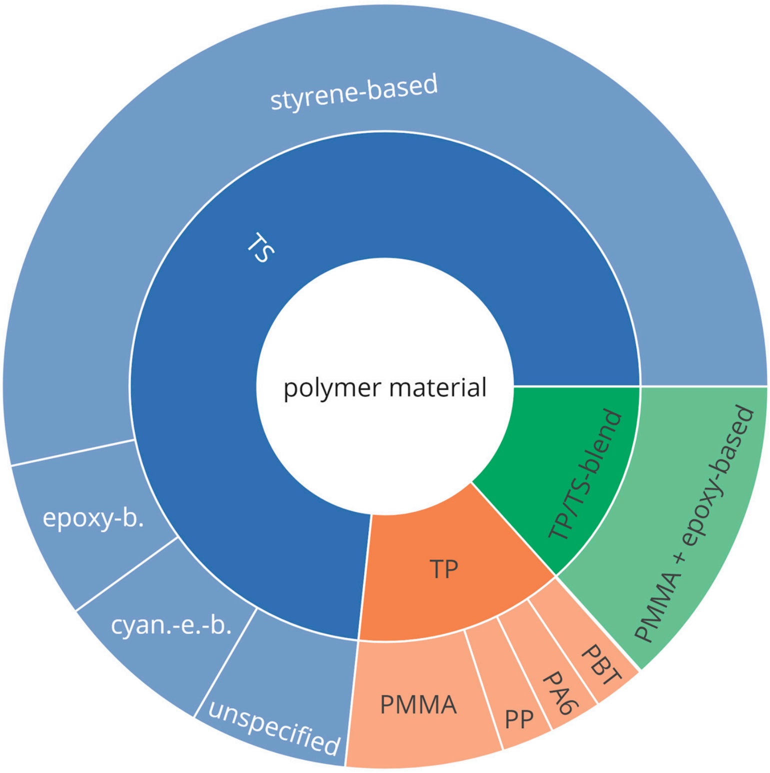

Figure 6. Polymers used in relevant studies.

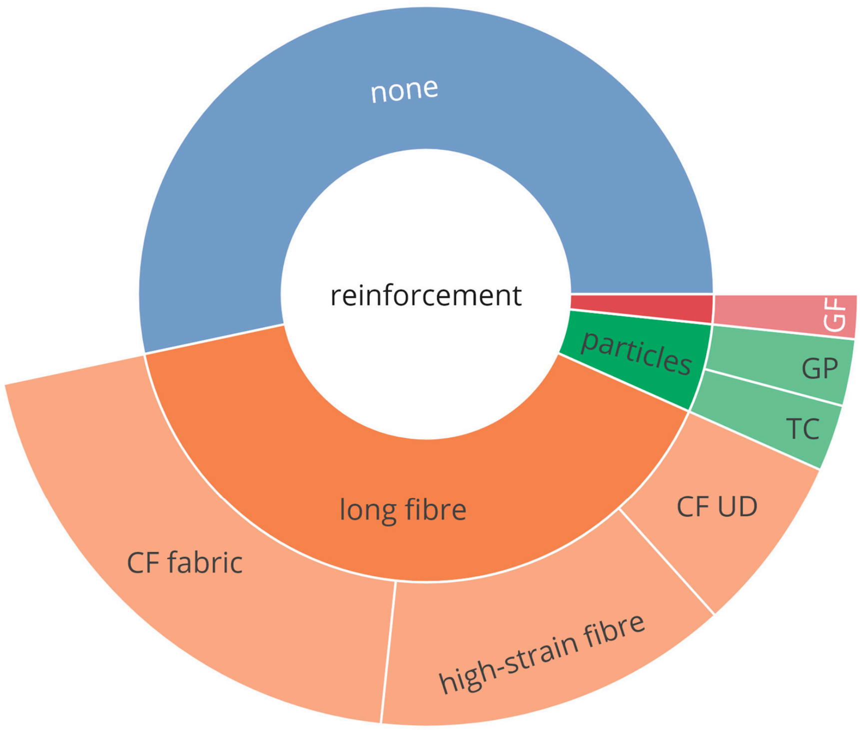

Figure 7. Reinforcement/fillers used in relevant studies.

3.2.3. Mandrel Manufacturing Process (RQ3)

Most papers cover liquid resins as semi-finished products, and casting is the most common method to manufacture the mandrel memory shape that is used in 67% of the studies. It offers an easy way to produce neat polymer mandrels, requiring only a cast and no additional equipment. The liquid resin is poured into the cast and cured. After the curing process, the temporary shape is programmed by heating the preform over the polymer glass transition temperature and expanding it using inner pressure in an outer rigid mold. The preform is then cooled down under the inner pressure and demolded from the outer rigid mold. Casting is used in all studies focusing on neat polymer mandrels and additionally in those by Li et al. (2019) and Lu et al. (2021) [14–16,19,20,44,46–49]. A disadvantage of casting is that the production of fiber-reinforced cores is limited, as sufficient impregnation of the fibers cannot always be guaranteed. This can result in voids and dry spots. An RTM (13%) or vacuum-assisted RTM (13%) process is much more complex than a casting process. In addition to the mold, production aids such as a vacuum pump, vacuum hoses and connections, and matrix lines and films are required. However, the process enables the production of fiber-reinforced mandrels without dry spots and voids. Jing et al. (2021) used RTM to manufacture their carbon fiber fabric-reinforced thermoplastic/thermoset-blend mandrel [50,51]. Pfledderer et al. [45] used vacuum-assisted RTM for manufacturing their high-strain fiber-reinforced mandrel. It is assumed that Everhart et al. (2006) [23] used a similar technique since their study was carried out in the same research group using the same reinforcement. Miadowitz (2019) [43] (7%) used extrusion blow-molding to manufacture his mandrels. Extrusion blow molding enables the production of thermoplastic hollow parts with a smooth outer contour from plastic granules at high rates. However, it requires an extruder, a blow-molding machine, and associated infrastructure, making it uneconomical to produce small quantities. The use of fillers in the plastic granules such as short fibers or powders is possible, but the use of long fiber reinforcements is not. Since the extruded preforms are expanded during the blow-molding process, no further process steps are needed thereafter. A generalized flow chart for the mentioned processes is shown in Figure 8.

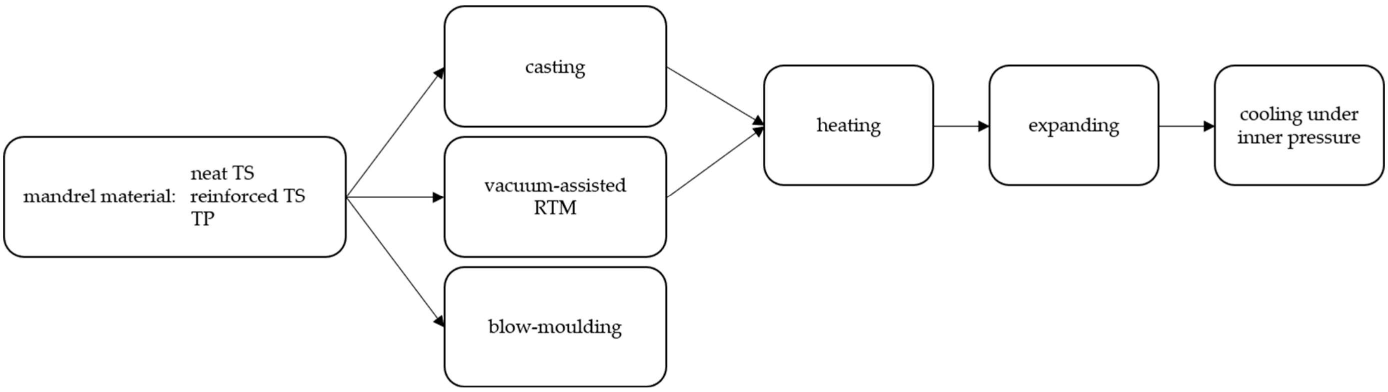

Figure 8. Flow chart of the manufacturing processes used in the relevant studies.

3.2.4. Composite Manufacturing Methods on Polymer Mandrels (RQ4)

Hollow composite profile manufacturing is highly associated with automated preforming methods such as filament winding, braiding, and fiber placement [13]. In case of wet winding and the use of towpreg or prepreg tapes, no further impregnation is needed. When dry fibers are applied, the preform has to be impregnated using RTM or vacuum-assisted RTM. As mentioned in Section 1, use cases are complex composite struts, air inlet ducts, or pressure vessels. Use cases and manufacturing methods investigated in the reviewed studies are sorted into Table 5. It is evident that the current research on variable shape tooling focuses especially on the automated manufacturing of inlet ducts and pressure vessels.

Table 5. Use cases and manufacturing methods investigated in the reviewed studies.

Use Case Manufacturing Method	Air Inlet Duct (47%)	Bottle-Shaped Composite Part (40%)	Complex Strut (33%)	Other or Not Specified (20%)
Filament winding (73%)	[15,20,44,46,48]	[15,19,44,48]		[23,49]
Fiber placement (33%)	[15,44]	[15,44]		[23]
Braiding (13%)			[43,45]	
Hand lay-up (20%)			[45,50,51]	

3.2.5. Shape Variability Activation (RQ5)

As shown in Figure 9, the shape variability in all considered studies (100%) is activated by heating. In all papers using thermoset materials (73%), the heating led to the activation of a shape memory effect as well as to the softening of the mandrel. Studies focusing on thermoplastic mandrels or those made of thermoplastics blended with thermoset resin only (27%) used the softening-through-heating effect to make the mandrel removable.

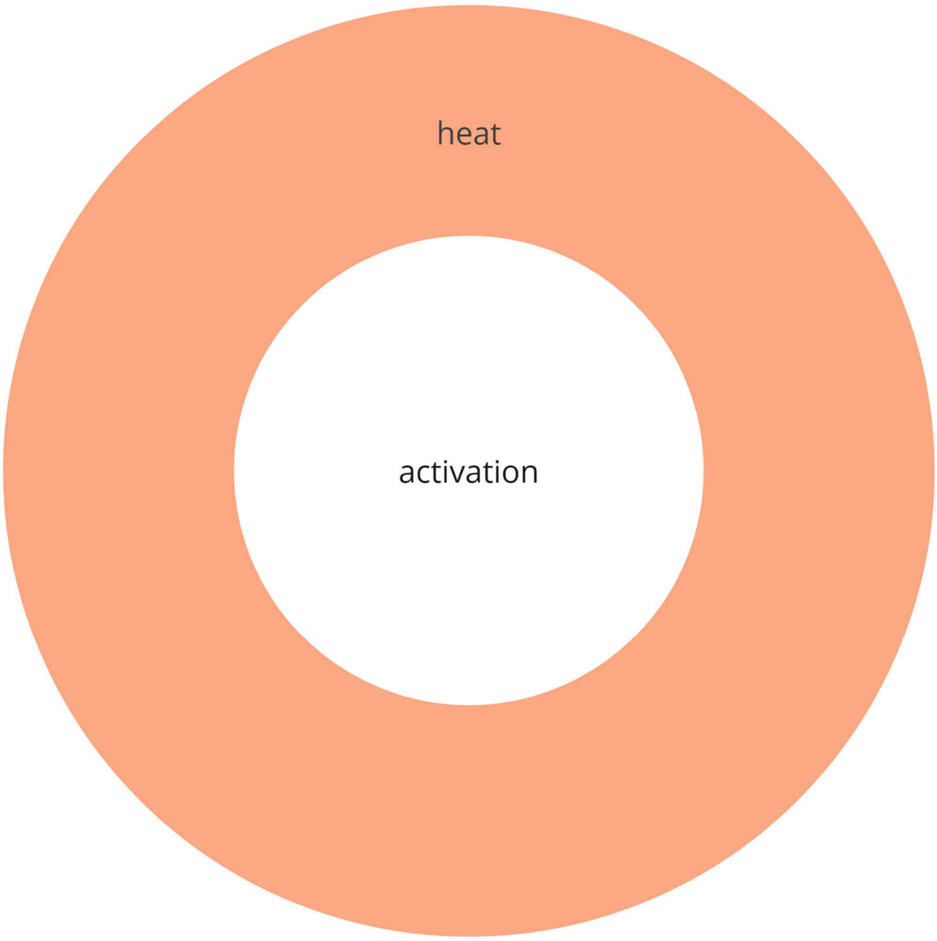

Figure 9. Shape memory activation method used in relevant studies.

3.2.6. Use of Release Agent (RQ6)

In 93% of the studies (14/15) in which composite components are manufactured, additional release agents were used. Du et al. (2015) [20] (7%) did their first manufacturing trials without a release agent and reported good demolding behavior. However, they recommend using a wax release film as the same research group did in Du et al. (2018) [46] (7%). In the remaining studies of this research group, no use of release agents is explicitly stated, but a paraffin layer was probably used (27%). Jing et al., Pflederrer et al., and Koury (27%) used an FEP film as a release agent in their studies [44,50,51]. Everhart et al. do not specify the use of a release agent. Since this work was published by the same research group in the same period of time, the use of an FEP film in the other 20% of the studies [15,19,23] can be assumed. Miadowitz (2019) [43] (7%) used release agents that were blended into the HP-RTM resin for composite part production. These findings are shown in Figure 10.

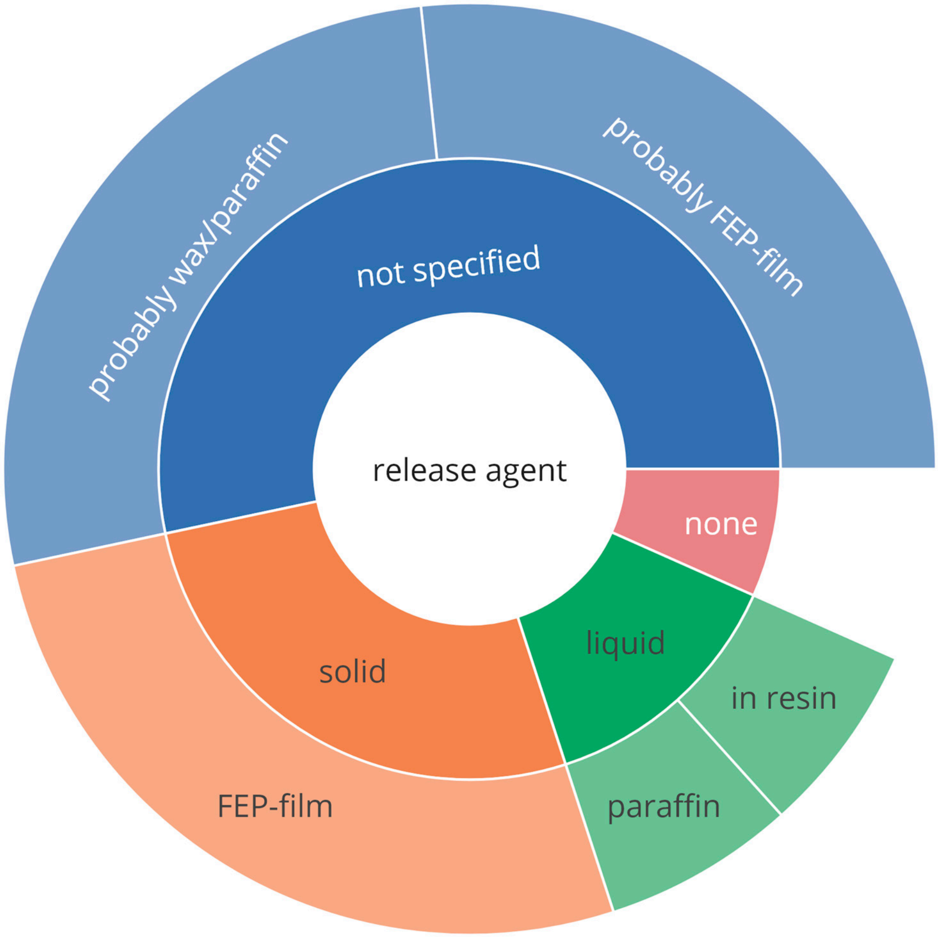

Figure 10. Release agent used in relevant studies.

3.2.7. Shape Variability Simulation (RQ7)

Only 27% (4/15) of the studies conducted a simulation of the manufacturing process with shape-variable mandrels. In [20], "finite element simulations are used to identify the total deformation and recover process and analyze the relationship between force and displacement." Therefore, a generalized Maxwell model was used. In [47], the "determined material properties were incorporated into the theoretical model [...] based on a phase transition model and generalized Maxwell model." In this way the generalized Maxwell model is used in 13% and the phase transition model in 7% of the studies. Miadowitz (2019) [43] (7%) simulated the blow-molding process and deformation under inner pressure of the mandrel during the HP-RTM manufacturing process using non-linear finite element calculations in ABAQUS. These findings are shown in Figure 11.

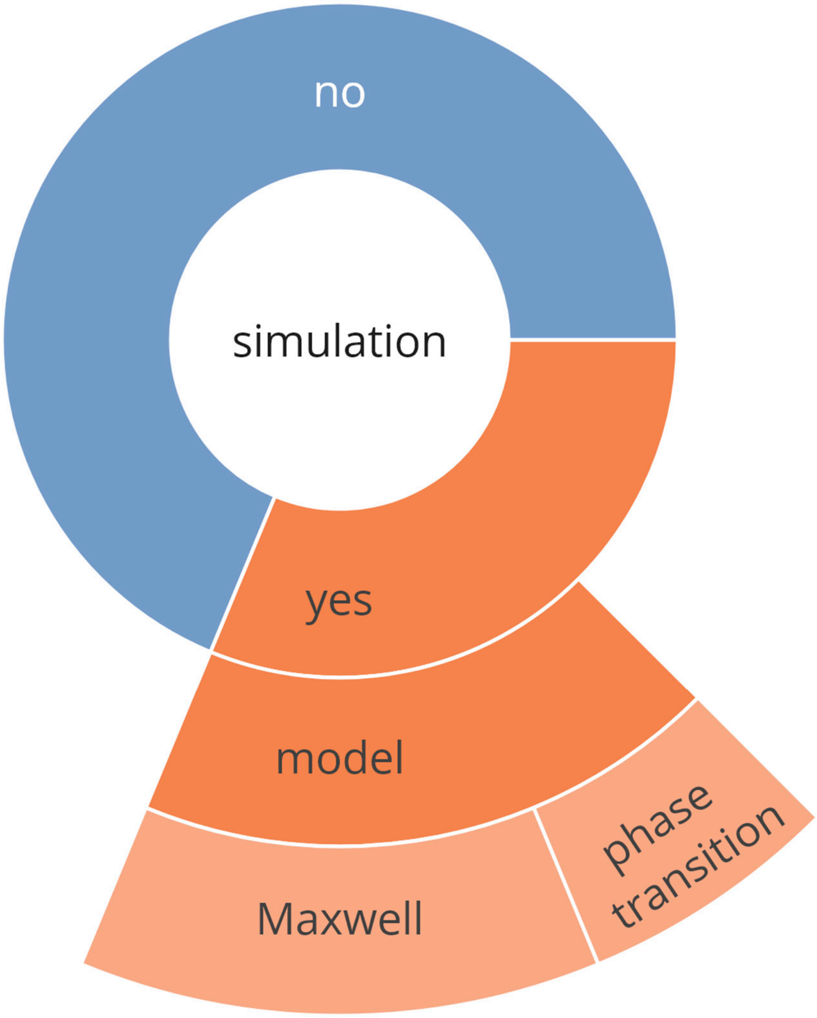

Figure 11. Simulation model used in relevant studies.

3.2.8. Mold Reuse or Recycling (RQ8)

All studies except [43] (93%) focus on reusable mandrels, which can be reformed for each production cycle. On the other hand, only in [46,50] (13%), the durability of the tooling regarding cycles is investigated. In [46] (7%), "the mandrels with diameter deformation ratios 25%, 50%, 75% and 100% could undergo 100, 38, 15 cycles and only one cycle before fail." In [50] (7%), 20 cycles were possible. Miadowitz (2019) [43] (7%) investigated single-use blow-molded mandrels, which are shredded after demolding and re-feed to the extruder. However, this material recycling was neither investigated nor assessed in comparison with reusable mandrels. These findings are shown in Figure 12.

3.2.9. Economic and Ecological Assessment (RQ9)

As shown in Figure 13, none (0%) of the examined studies assessed the economical or ecological advantages and disadvantages of shape-variable tooling in comparison to conventional tooling concepts. Some papers stated savings in both labor and production time but without any evidence.

3.3. Results: Relevant Studies

This section analyzes and summarizes the relevant studies one-by-one This allows for a deeper understanding of the single studies and makes them easily accessible. Furthermore, every publication is summarized in Table 6 with regard to the research questions. If a field is not applicable or not specified, it is left blank.

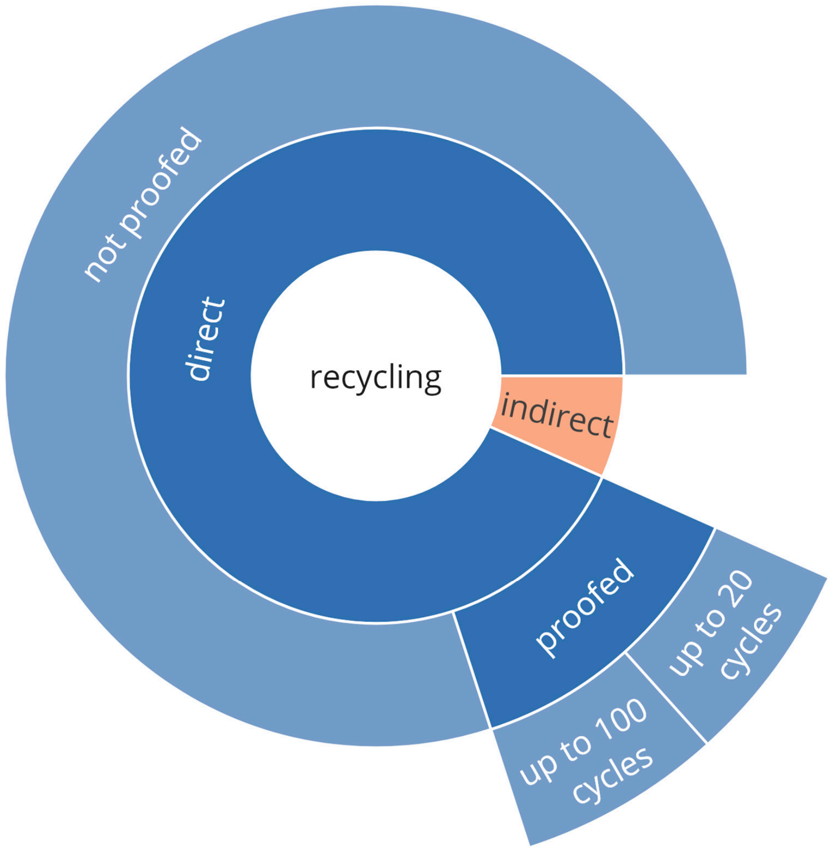

Figure 12. Recycling perspectives shown in relevant studies.

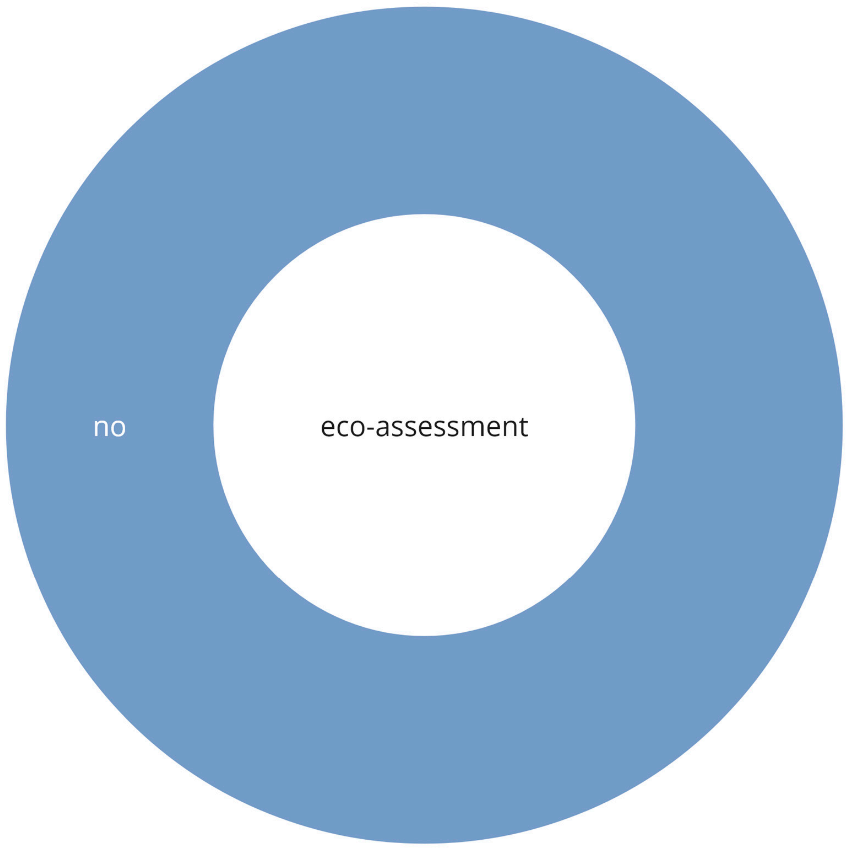

Figure 13. Eco-assessment method used in relevant studies.

Table 6. Summary of the relevant studies regarding the research questions.

Reference	Type of Polymer	Reinforcement	Release Agent	Manufacturing Process	Manufactured Item	Simulation Model
Du et al. [20]	styrene-based SMP thermoset	no reinforcement	no release agent	wet winding (CF + Epoxy)	s-shaped inlet duct mandrel + part	phase transition generalized Maxwell
Du et al. [14]	styrene-based SMP thermoset	no reinforcement	-	-	bottle-shaped mandrel	-
Du et al. [46]	styrene-based SMP thermoset	no reinforcement	paraffin release agent	wet winding (CF + Epoxy)	bottle-shaped mandrel + part	-
Du et al. [47]	two types of styrene-based SMP	no reinforcement	-	-	double bottle-shaped mandrel	phase transition generalized Maxwell
Everhart et al. [19]	styrene-based SMP thermoset	no reinforcement	release agent used (not specified)	casting/wet winding (Epoxy (+CF))	casting mold, bottle-shaped mandrel + part	-
Everhart et al. [15]	styrene-based SMP thermoset	no reinforcement	-	wet winding (Epoxy +GF/CF)	s inlet duct, bottle-shaped mandrel + part	-
Everhart et al. [23]	cyanate ester SMP thermoset	high-strain fiber reinforcement	-	-	sheet of reinforced SMP	-
Jing et al. [50]	PMMA + Epoxy + LNBR tp/ts blend	CF plain fabric	PTFE film	prepreg/autoclave	c-shaped mandrel + CFRP spar	-
Jing et al. [51]	PMMA thermoplast	CF fabric	PTFE film	prepreg/autoclave	c-shaped mandrel + CFRP spar	-
Koury [44]	styrene-based SMP thermoset	no reinforcement	PTFE film	filament winding/AFP autoclave cure	s inlet duct, bottle-shaped mandrel + part	forces during winding/AFP simulated
Li et al. [49]	epoxy-based SMP thermoset	CF (wound)	-	-	bending specimen	-
Lu et al. [16]	PMMA + Epoxy (+ LNBR) tp/ts blend	CF	-	-	-	-
Miadowitz [43]	PA, PP, PBT thermoplastic	neat, talcum, graphite, glass fiber strands	blended in resin	dry fiber braiding + HP-RTM	mandrel + CFRP hollow profile	pressurization and extraction of mandrel
Pfledderer et al. [45]	cyanate ester SMP thermoset	no reinforcement	FEP shrink tube	CF-prepreg and autoclave cure	mandrels + CFRP double i-beam	-
Zhang et al. [48]	styrene-based SMP thermoset	no reinforcement	-	filament winding	bottle-shaped, air duct-shaped mandrels	-

3.3.1. Du et al. (2015)—Composite Structures 133 [20]

The paper, Shape memory polymer S-shaped mandrel for composite air duct manufacturing, focuses on the design and modeling of an SMP air duct mandrel, featuring a circular end and a rectangular one at the opposite end. The primary focus of this paper is evaluating the deformation and recovery potential of an SMP mandrel prototype, along with analyzing the extraction process. Additionally, finite element simulations are employed to understand the overall deformation and recovery stages and examine the correlation between force applied and displacement. PAN-based carbon ribbon epoxy resin is used for part production. The part is then cured under rotation for 10 h at room temperature. For demolding, the mandrel is heated over its T_g of 80 °C by a heat gun. Therefore, it shrinks and becomes elastomeric. The mandrel reverts to its original shape and detaches from the inner surface of the composite part. A minimal pulling force is used on one end of the SMP, allowing for the extraction of the SMP mandrel from the composite part. A summary of the most important contents of the paper can be found in Table 7.

Table 7. Recovery ratios and maximum recovery stresses determined by Li et al. [49].

Fiber mass fraction	16%	23%	30%	37%
Reached recovery ratio @ 120 °C	96%	95%	93%	94%
Maximum recovery stress	16.5 MPa	24.3 MPa	39.6 MPa	49.0 MPa

3.3.2. Du et al. (2017)—Polymer Testing 57 [14]

In their follow-up research, *Thermal-mechanical behavior of styrene-based shape memory polymer tubes*, Du et al. analyze the mechanical properties of a fabricated SMP tube. The cast tubes inflate when heated over their T_g, to program the temporary shape. The tensile, compression, bending, and twisting deformation properties are investigated. The shape memory effect is activated by heating; thus, the SMP tubes become elastomeric and shrink. A summary of the most important contents of the paper can be found in Table 7.

3.3.3. Du et al. (2018)—Polymer Testing 69 [46]

In their next follow-up study, Shape retainability and reusability investigation of bottle-shaped SMP mandrel, Du et al. further investigate their SMP tooling regarding the surface accuracy, shape retainability, and reusability. The bottle-shaped mandrel is cast in a mold, cured, and afterwards inflated, while being heated over their T_g to program the temporary shape. The recyclability of mandrels with different diameter deformation ratios from 25% to 100% are investigated. One cycle consists of the programming of the temporary shape and activating it by heating, followed by its reforming. The working life of the SMP mandrel is significantly reduced with an increase in the deformation ratio. The mandrels with diameter deformation ratios of 25%, 50%, 75%, and 100% could undergo 100, 38, and 15 cycles and only one cycle before failure. The shape fixity ratios of SMP mandrels with different deformations remained above 98% with increasing cycles. A summary of the most important contents of the paper can be found in Table 7.

3.3.4. Du et al. (2019)—Composites Part B 173 [47]

In their study, Triple-shape memory effect in a styrene-based shape memory polymer: Characterization, theory and application, Du et al. investigated a segmented styrene-based SMP mandrel made from two types of neat SMP materials. SMP1 is cast and cured for 1 h. Then, SMP2 is added on top of SMP1 and fully cured in an oven at 75 °C for 24 h. A summary of the most important contents of the paper can be found in Table 7.

3.3.5. Everhart et al.—SPIE Proceedings 2004 (2004) [19]

In their study, Shape memory polymer configurative tooling, Everhart et al. investigated a neat styrene-based thermoset tooling. The polymer is processed into a sheet material and a tube. The semi-finished is then vacuum-bagged, heated over T_g, and formed into a temporary shape under either atmospheric or inner pressure. The tooling is heated over its T_g so it returns to its original shape and becomes elastomeric. It is then removed from the part by hand. A summary of the most important contents of the paper can be found in Table 7.

3.3.6. Everhart et al.—SPIE Proceedings 2005 (2005) [15]

In their follow-up study Reusable shape memory polymer mandrels, Everhart et al. investigate a neat styrene-based thermoset (Cornerstone Research Group, Miamisburg, OH, USA: Veriflex™) tooling. The material is cast into a tube. The semi-finished material is then vacuum-bagged, heated over its T_g, formed into a temporary shape under inner pressure. The mandrels are heated over their T_g so they return to their original shape and become elastomeric. The tooling is then removed from the parts by hand. A summary of the most important contents of the paper can be found in Table 7.

3.3.7. Everhart et al.—SPIE Proceedings 2006 (2006) [23]

In their next follow-up study, High-temperature reusable shape memory polymer mandrels, Everhart et al. investigated a mandrel made of a cyanate ester shape memory polymer. The reinforcement raises the toughness of the SMP, and this allows for elongation in the programming state of up to 40 percent. The material is capable to withstand a composite cure of 176 °C. Furthermore, the SMP has a fine tunable T_g range of 135 °C to 230 °C. The shape memory effect is activated by thermal stimulus. Heated over its T_g, the SMP becomes elastomeric and reforms to its permanent shape. The reinforced SMP is meant for multiple use in high-production-rate manufacturing. The cyanate ester SMP is stated as quick, easy, reusable, and low-cost compared to traditional toolings. It lacks the durability to endure a traditional high-production-rate manufacturing environment due to its low toughness. Furthermore, the use of cyanate ester SMPs reduces the maximum elongation from 100% to 40% when compared with low-temperature styrene-based SMPs. A summary of the most important contents of the paper can be found in Table 7.

3.3.8. Jing et al.—Aerospace 8 (2021) [50]

In their study, Thermoplastic Mandrel for Manufacturing Composite Components with Complex Structure, Jing et al. investigated a mandrel made of a cast thermoplastic blend. When heated above its T_g, the mandrel softens and collapses. The tooling can be used up to 20 times. Process boundaries are a T_g between 80 °C and 90 °C, a profile error within 0.5 mm, and an average porosity of the upper and lower halves of composite parts of 0.72% and 0.61%. A summary of the most important contents of the paper can be found in Table 7.

3.3.9. Jing et al.—AIAM Proceedings 2021 (2021) [51]

In their study, Influence of Deformable Mandrel Based Composite Part Forming Process on Part Forming Accuracy, Jing et al. investigated a double-curved c-shape spar tooling made by RTM from the blended matrix and carbon fiber. When heated above its T_g, the mandrel softens and collapses. After demolding, the mandrel can be reformed and reused. The process is limited by the mandrel's T_g of 105 °C, but manufacturing under internal pressure is also possible above this temperature. A summary of the most important contents of the paper can be found in Table 7.

3.3.10. Koury (2005)—SAMPE Journal 41 [44]

In his study, Composite tooling reusable mandrels, Koury investigated a tooling made of Veriflex™. The polymer is cast and cured into a hose. The mandrels become elastomeric and retract to the original pre-mandrel memory shape when heated above their T_g. The mandrels can be reformed and reused after demolding. The forces a reusable SMP mandrel experiences during conventional fiber placement and filament winding composite fabrication are calculated by simulation. A 50–80% cost benefit for complex-curved composites is stated but not verified. A summary of the most important contents of the paper can be found in Table 7.

3.3.11. Li et al. (2019)—Composites Part A 116 [49]

In their study, Bending shape recovery of unidirectional carbon fiber-reinforced epoxy-based shape memory polymer composites, Li et al. investigated an epoxy-based thermoset SMP. A reinforced plate is manufactured by pouring the SMP over wound CF (Toray T700SC-12K) with fiber mass fractions of 16%, 23%, 30%, and 37%. The reinforced SMP plate is then cut into bending test specimen. These are bent and then recovered by heating. The achieved recovery ratios and the maximum recovery stresses for different SMP composites are shown in Table 7. The stresses during the second cycle were 4–12% lower. The specimens can be deformed and reformed without losing their shape memory property. The maximum stress decreases after the first three cycles and stabilizes after 10 cycles. The epoxy-based SMP is stated to be less expensive to manufacture then other SMPs. A summary of the most important contents of the paper can be found in Table 7.

3.3.12. Lu et al. (2021)—Journal of Physics: Conference Series 2083 [16]

In their study, A thermoplastic resin matrix and its physical properties suitable for deformable mandrel, Lu et al. investigated a blend of a PMMA and an epoxy resin. The mass ratio of thermoplastic-to-thermoset resin is 4:1. When heated, the mandrel material softens und becomes demoldable. A summary of the most important contents of the paper can be found in Table 7.

3.3.13. Miadowitz (2019)—PhD Thesis TU Dresden [43]

In his PhD thesis, Beitrag zur Entwicklung blasgeformter Kernstrukturen für die Fertigung von CFK-Hohlprofilen, T. Miadowitz investigated blow-molded thermoplastic mandrels. The mandrels are manufactured by extrusion blow-molding. After curing, the mandrel is heated to 60–120 °C (depending on the used polymer's T_g); thus, it becomes soft and can be pulled out of the CFRP hollow profile. Therefore, a special pulling apparatus is introduced that extracts the mandrel with a pulling force of 650–3000 Newton. This extraction process as well as the water pressurization are simulated using Abaqus. After extraction, the mandrel can be shredded and used as an input material for the extrusion blow-molding process again. A summary of the most important contents of the paper can be found in Table 7.

3.3.14. Pfledderer et al. (2021)—SAMPE Nexus Proceedings 2021 [45]

In their study, Performance and durability assessment of shape memory polymer tools for closed composite structures, Pfledderer et al. investigated a thermoset. The tooling is manufactured by vacuum-assisted resin transfer molding and can be expanded up to 20% in two directions when heated over its T_g. In this study, the mandrels are exposed to 59 thermal cycles and 23 FRP-parts are fabricated with them. Fourteen of those parts were of good quality. It is assumed that the continued crosslinking in the SMP tooling increased the SMPs' T_g and modulus, which led to limited debulking capabilities. A summary of the most important contents of the paper can be found in Table 7.

3.3.15. Zhang et al. (2014)—Composites Part B 59 [48]

In their study, Analysis and design of smart mandrels using shape memory polymers, Zhang et al. investigated a cast SMP mandrel. The temporary state is programmed by heating and expanding the mandrels to a maximum elongation ratio of 25%. It is shown that the recovery ratio is almost 100% when the activation temperature is over T_g. The ratio decreases to 85% when the temperature is 10 K below T_g and to 50% when the temperature is 20 K below T_g. There is no shape recovery measurable when the activation temperature is 30 K below the glass transition temperature or lower. A summary of the most important contents of the paper can be found in Table 7.

4. Discussion

This review identifies 15 primary studies that focus on variable shape tooling for composite manufacturing. The vast majority of these studies focus on thermoset polymers as mandrel material, particularly styrene-based polymers. However, these materials lack the ability to be used at high process temperatures, which are necessary for high temperature resin systems used in structural aerospace applications. The introduction of cyanate-ester-based polymers by Everhart et al. [23] overcomes this drawback. All identified thermoset SMP molds are capable of recovering from their programmed shape to their original shape, with high shape recovery ratios close to 100%. However, studies focusing on thermoset–thermoplastic blends or solely thermoplastics use a softening-by-heating effect for demolding without utilizing a shape memory effect. An advantage of the blow-molded mandrels introduced by Miadowitz [43] is their ability to decouple the FRP production process from the number of mandrels on hand and the use of commodity polymers with established recycling capabilities. One mold in the blow-molding machine is sufficient to produce multiple blow-molded mandrels at high rates. Thermoplastic blow-molded mandrels with shape memory effect are a research gap and could potentially overcome the major drawbacks of the identified studies. They could combine readily available polymer materials, decouple mold volume and FRP production rate, and possess shape memory capabilities. In this way, further research on the application of internal stresses in blow-molded mandrels should be conducted. Especially for high-rate production scenarios, the use of single-use mandrels with intermediate shape recovery rates could be an economical solution, particularly for the production of small air inlet ducts. Additionally, Du et al. [20] demonstrated that processes that do not require release agents can reduce lead times and costs by minimizing the use of manufacturing aids and labor hours. This approach also promotes more sustainable FRP production by eliminating the use of toxic and harmful chemicals. However, none of the identified studies have conducted a comprehensive eco-assessment of the promoted technology. Further research is necessary to demonstrate the economic and ecological benefits of shape-variable tooling for FRP manufacturing. This research is essential during a time of heightened social awareness regarding climate change and waste management. It goes hand in hand with proved recycling capabilities of the promoted technologies. The identified literature lacks this topic since it was only investigated by Du et al. [46] and Jing et al. [50]. Efficient and easily accessible simulation models are necessary to design variable shape molds for the production of FRP. Only Du et al. [20,47] have shown simulation approaches on shape variability. Furthermore, research should focus on gaining a deeper understanding of the visco-elastic material modeling of polymers used for shape-variable tooling and on making those models more user-friendly for mold designers. Overall, this paper identifies three potential research gaps: (1) a comprehensive ecological and economical assessment of shape-variable mandrels in comparison to conventional tooling; (2) the use of thermoplastic shape memory polymer mandrels; and (3) a further investigation into simulation capabilities for shape memory mandrels. Research on these topics has the potential to contribute to molds that are easy to design and produce at high rates, leading to more sustainable FRP production.

This study represents the first systematic literature review on variable shape tooling for composite manufacturing. The aim of an SLR is always to be fair and thorough. In this regard, this review provides a full overview of studies on removable and reusable cores, which can be used as a mandrel for automated production processes of hollow composite profiles with undercuts, to the best knowledge of the author. The SLR followed the methodology by Kitchenham [32] and adapted the protocol proposed by van Dinter et al. [33] and Jilke et al. [34]. The proposed search string was continuously improved by iteration, aiming for the highest possible recall and precision. Since these properties are not necessarily coherent, there is a minimal risk that a slightly different search string could have produced slightly better search results. Using *ASReview*, the selection of primary studies was automated using natural language processing and machine learning. The termination condition used (100 irrelevant labeled studies) is rather conservative. This condition could have been reduced to 50 or even 20 irrelevant studies, with a slightly higher risk of missing out relevant studies. Van Dinter et al. [52] determined a termination condition of 10 irrelevant studies in a row to be sufficient. Since this study only used *ASReview* as a tool, it relies on the proven functionality by van de Schoot et al. [35]. To the best knowledge of the author, the usage of *ASReview* as well as the identified relevant studies provided no indication of a malfunction in the software. As shown by the PhD thesis of Miadowitz, it is possible that highly relevant studies were not published in journals or at conferences. For this reason, the automated search in the mentioned venues in this study was extended by manual search and snowballing. No further relevant studies could be identified using these methods. All conclusions were drawn from the retrieved and synthesized data to maintain an objective interpretation of the results.

5. Conclusions

A preliminary search for secondary literature was carried out showing a research gap since no thorough review of shape-variable tooling in composite manufacturing could be found (see Section 2). Consequently, a systematic literature review supported by the open-source active learning tool *ASReview* was conducted and evaluated on the topic: variable shape tooling for composite manufacturing. In Section 2.2, a search strategy for the SLR was developed. A search string was constructed regarding the defined research questions. Next, an automated search in six scientific literature databases was conducted. A total of 10.186 studies were found and filtered based on their title and abstract using the defined exclusion criteria. In total, 760 studies were labeled using *ASReview*. Moreover, 58 studies were labeled relevant. After applying the exclusion criteria to the full papers, 15 studies remained relevant. These studies were analyzed based on their content and meta-data in Section 3. Three main research groups could be identified in the USA and the PRC, accounting for 14 of the 15 relevant studies. The extracted content data were then used to answer the defined research questions. It was found that (1) tooling is mostly made of unreinforced thermosets, especially styrene-based ones; (2) thermoplastic resins are less common, and reinforcements limit the usable elongation in the temporary shape; (3) the shape variability is either a shape memory and/or a softening process, which in all studies is activated by heating; (4) release agents are widely used to ease demolding; and (5) no ecological or economical assessment of the manufacturing method was conducted in the reviewed studies. Furthermore, it was found that no research was conducted on shape memory mandrels made of thermoplastics. Finally, three possible research gaps can be identified: (1) thorough ecological end economical assessment of shape-variable mandrels in comparison with conventional tooling; (2) thermoplastic shape memory polymer mandrels; and (3) further investigation of simulation capabilities for shape memory mandrels. Overall, shape-variable mandrels are a promising solution for the high rate of production of complex hollow composite profiles with smooth inner surfaces such as air inlet ducts, pressure vessels, or struts. Follow-up research should investigate the possibility of thermoplastic shape memory mandrels and their simulation capabilities. A thorough economic and ecological assessment is necessary to show the meaningfulness of SMP tooling in comparison with conventional tooling in specific production scenarios based on open and accessible data.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jcs-2897626/s1, , File S1: PRISMA_Checklist_FNeumann.PDF; File S2: PRISMA_Flowdiagram_FNeumann.pdf

Funding: This research received no external funding. The research was carried out within the framework of the German Aerospace Center's core funded research.

Acknowledgments: Special thanks to Lukas Jilke from German Aerospace Center (DLR), Institute of Maintenance, Repair and Overhaul, for an introduction of Systematic Literature Reviews and for helping with the use of ASReview.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Conflicts of Interest: The author declares no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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