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Classifying Parameters and Target Variables in Incremental Sheet Forming of Fiber Reinforced Polymers

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Abstract. Incremental Sheet Forming (ISF) enables the flexible creation of shell-shaped structures. Unlike conventional forming, ISF does not require a bespoke forming tool, greatly reducing upfront costs and lead times, especially for small lot sizes. Several parameter classifications for the ISF of metals and polymers have been proposed in the past. Such classifications increase awareness of possible levers for process optimization, guide experimental analysis, and enable a holistic understanding. Lately, fiber-reinforced polymers (FRP) are of increasing interest in ISF. In previous studies, ISF systems for various kinds of FRP have been developed, and several parameters and target variables have been investigated. However, there is currently no classification that addresses the specific parameters and target variables relevant to this material class. Therefore, the goal of this work is to develop such a classification to create a comprehensive foundation for future FRP ISF investigations. This effort is undertaken by building upon existing classifications and reviews independent of the material class and synthesizing these with a systematic literature review of FRP ISF investigations. The resulting classifications cover a broad range of parameters and target variables and reveal a structure that guides a systematic understanding and ensures future expandability.

Introduction

Incremental sheet forming (ISF) has been extensively studied as a flexible alternative to conventional forming processes relying on molds [1]. The dieless manufacturing process uses part-agnostic, often hemispherical tools to incrementally generate the desired target shape [2]. This greatly reduces upfront investment costs and lead-times, making it particularly interesting for small series, prototypes, and highly individualized parts. Most ISF investigations up to this point have addressed metals and later polymers. Research in these domains has identified a vast space of relevant parameters to understand and optimize the process. Multiple classifications have been developed to structure this space and to capture and compare process variants and parameters [3-5].

In recent years, ISF has also been applied to the material class of fiber-reinforced polymers (FRP). These high-performance lightweight materials are common in industries like aerospace, performance sports, and orthopedics [6]. In these industries, the need for flexible production processes is widespread, making ISF a promising pathway. The first study on the ISF of FRP was published more than a decade ago [7]. In recent years, reviews on the broader material class of composites, with a focus on structural metal, polymer, and metal-polymer composites, have also included works on FRP [8, 9]. However, there currently exists no structured classification of the space of parameters and target variables that could provide a comprehensive foundation for the analysis of this process. Classifications exist especially for metal ISF, but key differences in the material behavior cast doubt on the transferability of knowledge to FRP. To establish a classification that is suited for the ISF of FRP, this work starts with an analysis of the content and structure of existing classifications and reviews. This basis is combined with a quantitative and qualitative systematic literature analysis of FRP ISF.

Based on structural observations in existing classifications, the content of previous reviews, and the parameters and target variables found in the FRP ISF literature, a classification of parameters and target variables is developed, specifically tailored to this material class.

Methods

Following the analysis of existing overviews on composites as well as other material classes, the landscape of individual studies on FRP ISF is systematically reviewed. The goal of this review is to identify the structure, parameters, and targets relevant to past research efforts on this topic. The review is performed on the databases Scopus and Google Scholar. The search string logic is provided below, with the search strings for Scopus and Scholar being only adjusted in syntax.

The title includes at least one of: SPIF, DSIF, ISF, Incremental Forming, Incremental Sheet Forming, Pin Forming, Shell Shaping, Dieless, Mould*Free AND at least one of: composite*, fibre*, fiber*, cfr*, textile*, fabric, organo AND the document is either a paper or an article.

Literature is included for further analysis if the following criteria are met: Fiber-reinforced material is used, parts are directly manufactured in an ISF process in a narrow sense (i.e. not multistep forming, modular molds or in-situ consolidation), and the papers are written in the English language. Of the works meeting these inclusion criteria, only those performing some real-world experiments are included in the subsequent quantitative analysis. Works that are solely conceptual, designs, or numerical studies are still included in the qualitative analysis to identify characteristics that might emerge from the overall solution space.

Following execution of the search strategy, 66 sources on Scopus and 89 results on Google Scholar match the search string. The last search was performed on November 7, 2025. After screening titles and abstracts based on the defined inclusion criteria, 29 unique sources are retained for further analysis. Of these, 25 are included in the quantitative analysis, while four are considered only in the qualitative assessment because they reported no real-world experiments. For the quantitative analysis, the factors studied in each work, the target variables, the materials used, and the type of experiment performed are extracted manually, along with the year of publication. The subsequent categorization and evaluation of parameters and targets are supported by custom Python scripts.

Based on the analysis, the initial lists of targets and parameters obtained from the ISF overviews are expanded by those found in the FRP literature. Based on ideas found in metal ISF classifications and the previous analysis, a unifying taxonomy is created that captures the parameter and target spaces of FRP ISF, and insights derived from this structure are discussed.

Analysis of Existing Overviews

Parameters.

Seven existing ISF overviews are selected to be representative of a variety of perspectives to cover both a wide range of relevant parameters as well as different classification structures. Two are recent and application-driven works that present very elaborated classifications: In Vanhulst et al. [5] the classification is presented as part of a large benchmark study and the one found in Bremen et al. [10] serves to set up an experimental data base. These two works present comprehensive classifications, but are mainly concerned with the ISF of metals. Two additional works presenting classifications are analyzed that in addition to metals also consider the ISF of polymers [3, 4]. While the works mainly concerned with metal ISF provide the most elaborated classifications in both structure and content, they are also the furthest from FRP in regards to its material behavior. For this reason, further reviews are included: One which specifically addresses ISF for thermoplastics [11] and two which address ISF of composites (including metal-metal and metal-polymer composites) [8, 9]. These reviews do not provide complex classification structures and cover a limited number of parameters, yet provide valuable insights into the material-specific parameter spaces.

In the following, these seven overview publications will be analyzed regarding their structure to identify commonalities that might inform the structuring of an FRP ISF classification. Following the structural analysis, the content of the classifications is extracted and synthesized to form a unified parameter list that will serve as a basis for the parameter list created for the FRP ISF classification.

Aside from the content, an important aspect of any classification is its structure. The classifications found in the existing literature vary in both structural complexity and specificity. Some only list a number of classes or parameters [3], some show more complex taxonomies [4, 5, 10]. The most elaborate structure is found in Vanhulst et al. [5] and Bremen et al. [10], who describe three similar top-level classifications or domains. These are Platform, Workpiece, and Process (Vanhulst), and Process, Product, and Tool & Parameters (Bremen). The majority of the parameters in the Platform domain in Vanhulst et al. and in the Process domain in Bremen et al. consist of the machine description. Product and Workpiece domains of the two different studies can be directly identified with each other. Lastly, the Process parameter domain in Valhulst et al. has a large overlap with the Tool & Parameter domain in Bremen et al., including tool path and movement parameters. Kumar et al. [4] take a different approach of differentiating between classifications for the general process, warm forming techniques, the toolpath, and process parameters. McAnulty et al. [3] do not include any subclassifications in their framework but provide a list of important parameters. Similarly, the reviews addressing thermoplastic and composite materials do not propose any specific classification at all but include parameter lists [8, 9].

Regarding the content of the classifications, *Table 1* will be used as a guide throughout this work. First, the parameters from existing overviews are collected in columns one to three. Later, the parameters from the FRP ISF literature are collected in columns four and five. Finally, the remaining columns document the additions and modifications to the list collected from the overviews that transform it into the final list of parameters included in the developed classification.

Table 1. Parameters from overviews (col. 1-3) and FRP ISF literature (4+5) with number of publications (NoP); Modifications made to form the content of the classification (right side).

Existing Frameworks NoP>1	NoP	Existing Frameworks NoP=1	FRP ISF Works	NoP	Added Parameters	Removed Parameters
Step Size	7	Anisotropy	Temperature	9	Area Weight	Layer Arrangement
Initial Sheet Thickness	6	Application Frequency	Step Size	7	Back Sheet Material	Forming Side
Spindle Speed	6	Application Method	Maximum Wall Angle	7	Back Sheet Thickness	Material Type
Tool Size	6	Axis Config	Fiberorientation	5	Back Side Pressure	Sheet Material
Feed Rate	5	Backing Plate Details	Fiber Volume Fraction	3	Clamping Force	
Forming Temperature	5	Deepest Cavity	Path Type	3	Components being Clamped	Replaced Parameters
Maximum Wall Angle	4	Forming Orientation	Layup	3	Cooling Ramps	Reinf. Weight Fraction
Forming Method	3	Forming Side	Tool Size	3	Fiber Geometry	Forming Temperature
Forming Strategy	3	Geometry Features	Temperature Distribution	2	Fiber Material	Forming Force
Tool Shape	3	Input Sheet Geometry	Initial Sheet Thickness	2	Fiberorientation	Heat Source
Toolpath Type	3	Material State	Spindle Speed	2	Front Sheet Material	Material State
Type of Heating	3	Material Type	Temperature Ramps	1	Front Sheet Thickness	
Clamping Geometry	2	Reinforcement Weight Fraction	Fixture	1	Front Side Pressure	
Forming Force	2	Superimposed Shape	Cooling	1	Heating Ramps	
Layer Arrangement	2	Symmetry	Feed Rate	1	Matrix Material	
Load Capacity	2	Temperature Distribution	Oilbath	1	Reinforcement Struct. Details	
Lubrication Type	2	Tensile Strength			Reinforcement Struct. Type	
Machine Stiffness	2	Tightest Radius			Seperator Material	
Machine Type	2	Tool Coating			Seperator Thickness	
Part Dimensions	2	Toolpath Direction			Storage Condition	
Part Shape	2	Type of Preform Fabrication			Support Angle	
Positioning Accuracy	2	Youngs Modulus				
Sheet Material	2					
Spindle Rotation Direction	2					
Tool Material	2					
Tool Type	2					
Work Space Size	2					

For now, a total of 102 uniquely named parameters is extracted from the overviews. After unifying the naming conventions and dissolving and summing to specific or general parameters, 49 unique parameters remain. These are listed in the first and third columns of Table *1*. Only the 27 parameters shown in the first column of Table *1* occur in more than one classification, with the number of publications (NoP) covering each parameter shown in the second column. Only seven appear in more than half of the overviews, which are Step Size (100\%), Initial Sheet Thickness (85.7\%), Spindle Speed (85.7\%), Tool Size (85.7\%), Feed Rate (71.4\%), Forming Temperature (71.4\%), and Maximum Wall Angle (57.1\%). It is also apparent that none of the overview publications is exhaustive. The highest number of leaves is found in Bremen et al. [10], who cover 30 of the total 49 parameters synthesized from all overviews.

Target Variables.

In the analysis of target variables in the existing overviews, there is no classification to be found that would warrant a structural analysis comparable to that of the parameters. Still, an important distinction can be found between target variables and failure criteria. While the former are similar across the different material types, the latter differ greatly between them. The goal of the following section is to collect the target variables and failure criteria found in the overviews to later combine these with the systematic analysis of the FRP ISF literature to develop a FRP ISF suited classification. Similar to the parameters, the targets are collected within Table *2*, with the first three columns regarding the overview publication and the last being reserved for the later analysis of the FRP ISF literature.

In metal ISF, McAnulty et al. [3] focused their review on part formability, represented by the formable wall angle. As a side note, they also mention surface quality, geometric accuracy, resulting material properties, and the forming force as further possible targets, though they are not further investigated. Kumar et al. [4] concerned their analysis particularly with the forming force. Bremen et al. [10] and Vanhulst et al. [5] address five major outcomes or challenges in ISF, that, although using slightly differing names, describe very similar targets. One is the forming limit or producibility of the part, which is associated with the wall angle. Another is the thinning of the sheet, which precedes its failure. The geometric accuracy is also addressed in both works, which is further differentiated into elastic and plastic deformation. The surface quality or finish is the last part-related target. Process time, or more generally, productivity, is the last overall target mentioned in both works. Aside from these, Vanhulst et al. also address specific effects impairing the process outcome, namely the tent and pillow effects, as well as the occurrence of corner folds.

Table 2. Target Variables from overviews and FRP ISF literature.

Targets in the existing overview literature			Targets in FRP ISF
Metal	Thermoplastics	Composites	
Formability	Formability	Formability	Wall Angle
Wall Angle	Wall Angle	Wall Angle	Forming Depth
Surface Finish	Surface Finish	Forming Depth	Surface Finish
Geometric Accuracy	Geometric Accuracy	Surface Finish	Geometric Accuracy
Material Properties	Void Content	Geometric Accuracy	Thickness Distribution
Forming Force	Chain Orientation	Spring Back	Shrinkage
Thinning	Force	Mechanical Strength	Pull-In
Process Time	Energy	Fatique Properties	Mechanical Strength
	Cost	Force	Voids
			Force
Failure Modes / Criteria			
Necking after Thinning	Oblique Cracks	Oblique Cracks	Tearing
(Pillowing)	Circumferential Cracks	Circumferential Cracks	
(Corner Folds)	Wrinkling through Twisting	Wrinkling	Wrinkling
		Bulging	Bulging
		Excessive Void Formation	Deconsolidation
		Delamination	Delamination

In thermoplastic ISF, Zhu et al. [11] name similar target variables, namely formability, accuracy, surface finish, force, energy, and cost. Yet, the mechanisms influencing some of these targets differ: Regarding formability, although they also name wall angle as a primary metric, they identify two failure modes that are not present in metal ISF. These are the wrinkling as a result of a twist in the part, resulting from the tool movement, as well as an oblique fracture in the wall area. They also point out that in-plane fracture occurs, but without the preceding necking observed in metals. They also address the microstructure of the material, particularly the void content and chain orientation. While the quality targets are otherwise similar, they additionally name economic cost and energy consumption as target variables.

Liu et al. [8] describe similar material-dependent failure criteria for composites as for neat polymer, namely, circumferential and oblique cracks. In addition to these failure criteria, they point out the importance of wrinkles not just through global twisting, but also caused during the forming of woven reinforcements. Voids and delamination are added to the list of possible failure criteria. Still, maximum drawing angle and depth are mentioned as the main formability metrics. Forming quality is differentiated into accuracy, surface quality, mechanical strength, and fatigue properties. The forming force is also designated as a target.

Hussain et al. [9] classify wrinkling, rupture, and bulging as the main failure modes in reinforced composites. Aside from formability, they looked at force, springback, geometrical accuracy, and surface quality.

Review of Investigations on FRP ISF

The goal of this section is to systematically review the FRP ISF literature to identify the parameters and target variables currently investigated and varying between investigations. These will then be used to judge the applicability of findings from the overview literature to this material class and to identify necessary adjustments and additions. Special attention is given to the materials investigated within the scope of FRP ISF, as these differ significantly between investigations.

The 25 studies selected for the quantitative analysis are listed in Table *3*, together with key contents, which shall serve as a reference for the following analysis. It is to be noted that the materials, parameters, and target variables listed and analyzed are already terminologically unified and might differ from the wording used within individual publications. Additionally, only those aspects of the listed publications that directly address the incremental sheet forming process are analyzed. Any auxiliary experiments, material testing, and so forth are therefore excluded.

Table 3. Studies on FRP ISF and the materials, parameters, and targets investigated in each.

Ref.	Author	Year	Matrix	Fiber	Structure	Parameter	Targets
[7]	Fiorotto	2010	Epoxy	Glass	Woven	Layup	Tear
[12]	Ikari	2016	PA6	Carbon	Short	Path Type, Cooling	Tear, Surface Quality (Metldown)
[1]	Conte	2017	PA6	Glass	Short	Temperature, Step Size, Wall Angle	Shrinkage, Thickness
[13]	Okada	2017	PA6	Carbon	Short		Geometry
[14]	Okada	2018	PA6	Carbon	Short	Initial Sheet Thickness, Tool Size	Geometry
[15]	Ambrogio	2018	PA6	Glass	Short	Wall Angle, Step Size, Temperature, T-Ramp	Tear, Geometry, Shrinkage, Thickness
[16]	Al-Obaidi	2019	PA6	Basalt	Woven	Layup, Wall Angle	Delamination, Voids
[17]	Al-Obaidi	2019	PA6	Glass	Woven	Temperature Distribution	Wall Angle, Tear, Voids, Pull-in
[18]	Kubit	2019	Epoxy	Glass	Woven		Strength
[19]	Torres	2020	Solanyl	Glass	Short	Step Size, FVF, Temperature, Wall Angle	Depth
[20]	Hou	2020	PLA	Natural	Woven	Path Type, Fixture, Step Size, Initial Sheet Thickness	Depth, Surface, Bulge
[21]	Xiao	2021	Epoxy	Carbon	Woven	Fiber Orientation	Wrinkles
[22]	Emami	2023	PA6	Glass	Layup	FVF, Temperature, Fiber Orientation	Thickness, Geometry, Depth
[23]	Bagheri	2023	PA6	Glass	Short	Temperature, Spindle Speed, Step Size, Wall Angle	Depth, Shrinkage
[24]	Xu	2023	Epoxy	Carbon	Woven		Tear, Shear, Pull-in
[25]	Tanaka	2023	TP	Carbon	Short	Temperature	Geometry, Tear
[26]	Kalaei	2024	PA6	Glass	Woven	FVF, Temperature, Step Size, Fiber Orient.	Depth
[27]	Rath	2024	SAN	Carbon	Woven	Path Type	Wrinkles, Tear
[28]	Nettig	2024	PA6	Carbon	Nonwoven	Tool Size, Temperature, Temperature Distribution	Depth, Deconsolidation
[29]	Sun	2024	PP	Carbon	Layup	Temperature, Fiber Orientation	Geometry, Wall Angle, Depth
[30]	Ikari	2024	PA6	Carbon	Short	Spindle Speed, Wall Angle, Feed Rate, Step Size, Oil Bath	Geometry, Surface
[31]	Rath	2025	Vitrimer	Carbon	Layup		Tear
[32]	Xu	2025	Epoxy	Carbon	Woven	Layup, Tool Size	Wrinkles, Tear
[33]	Formisano	2025	PP	Natural	Woven	Fiber Orientation, Wall Angle	Force, Depth
[34]	Kallai	2025	PA12	Carbon	Woven		Geometry, Deconsolidation

Materials.

The materials used in FRP ISF must be distinguished into the FRP itself and, possibly, multiple other layup constituents. The FRP can be described by its matrix material, its reinforcement material, and the reinforcement structure. Four main structures have been investigated in FRP ISF so far. As seen in Fig. *1* a), the most prevalent is the use of woven reinforcements, which were investigated in

49\% of studies. The next most studied are short fiber reinforcements with 36\%. Laminates composed of unidirectional layers and nonwoven long-fiber reinforcements have been investigated in only a few studies (12\% and 4\%, respectively). Details of the reinforcement structure are, notably, often not stated in the literature. For example, the weave type or the method of preform fabrication could affect the process, but are not always included in its description.

The type of fiber is also crucial for the material behavior. Fig. *1* shows carbon and glass fibers to be the dominant materials used, with 52% and 36% of works, respectively. Only a few investigations so far address natural or inorganic fibers. While the fiber material is defined in all studies, the fiber geometry is rarely described. For discontinuous reinforcements, the fiber length has a significant influence on the material properties [35], yet it is almost never recorded in the publications.

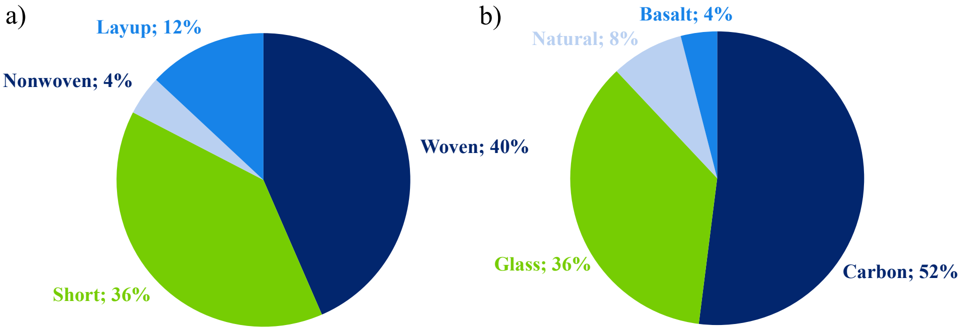


Fig. 1. Reinforcement structures a) and fiber materials b) by percentage of publications.

The studies on thermoset matrix materials usually just mention using epoxy resin-based systems. In studies on thermoplastics, the polymer used is reported in all but one investigation [25]. As illustrated in Fig. *2*, thermoplastic matrix materials have been studied in 76% of works, with Polyamide 6 being the most prominent, accounting for over 60% of thermoplastic studies. Other polymers used are Polypropylene [29, 33], Styrene Acrylonitrile [27], Solanyl [19], Polylactic Acid [20], and Polyamide 12 [34]. To date, one study has investigated the incremental forming of vitrimers [31]. A parameter often not mentioned in the studies is the description of the storage condition before the forming procedure. Especially for hydrophilic polymers such as polyamides and non-shelf-stable thermosets, this information can be crucial for interpreting results and ensuring reproducibility.

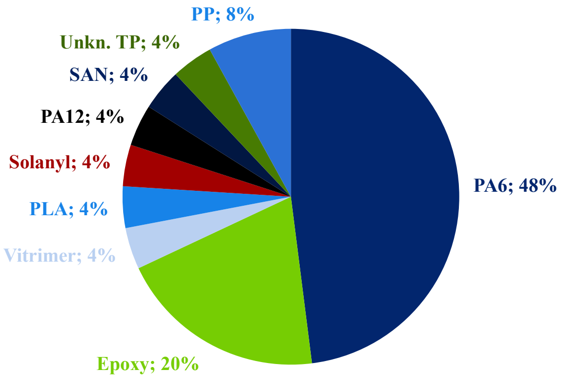


Fig. 2. Matrix materials by percentage of publications.

In addition to the composite material itself, some of the processes employ additional metal sheets. This is most common with continuous fibers, where all but one publication [33] used metal dummy sheets, most often with a quasi-floating clamping of the composite to allow the pull-in required for its deformation. Although less commonly, metal sheets have also been used with short fiber reinforcements [1]. The materials used for the dummy sheets may differ between the sides of the composite sheet [32]. When the composite and metal are not meant to be bonded together, a separator, like thin Polytetrafluoroethylene foil, has been used [17, 20, 27].

Parameters.

Although FRP ISF is a comparatively new field with a total of just 25 works being included in this quantitative assessment, a surprisingly large number of 16 unique parameters has been investigated so far (see Table *1*). There is some overlap between the parameters studied in the FRP ISF literature and the parameters synthesized from the overviews. However, a wider variety of workpiece and temperature-related parameters has been studied: Aside from the forming temperature, there are also investigations on the temperature distribution, temperature ramps, and active cooling methods. The initial sheet thickness and maximum wall angle are mentioned in a large number of publications, just as in the overview literature. However, the influence of other workpiece properties, such as fiber orientation, fiber volume fraction, and layup configuration, is also frequently investigated. In comparison, only relatively few and standard process and platform-related parameters have been studied so far, namely step size, spindle speed, feed rate, tool size, path type, and fixture type. Except for the fixture type, these are all part of the 27 parameters listed before. Without the tool path type and including sheet thickness, wall angle, and temperature, they make up the seven most prevalent parameters in the existing overview literature. In conclusion, the parameters from the existing ISF literature remain relevant to FRP ISF, and, in particular, process- and platform-related parameters are largely covered by at least some existing frameworks. However, especially for workpiece- and temperature-related parameters, the parameter space should be expanded to include the already studied parameters.

From a qualitative review of the literature, it is evident that a wide range of process configurations, including SPIF [27], TPIF [21], and DSIF [32], have been employed in single- [20] and multi-step processes [22] (i.e., multi-stage toolpaths where the final geometry is approached through several successive forming passes). While heating is always used in some form, a wide range of application methods has been explored in global [17] and local [14] heating schemes. The works omitted from the quantitative analysis indicate that the solution space continues to grow. A Hot-DSIF system with force-controlled support has been developed [36], as well as concepts to use hydrostatic pressure as a back-pressure support [37]. While only studied numerically, the initial blank outline has also been varied in one publication [38].

Based on this analysis, combined with the previous section on the materials used in FRP ISF, a list of 20 parameters not found in the overview literature is derived and listed in column six of Table *1*. In the following, it will further serve as the foundation for the development of an FRP ISF suited parameter framework.

Target Variables.

The FRP ISF literature also shows a wide variety of investigated target variables, with a total of 15 unique targets being investigated in the 25 works. While there is some overlap among targets, such as geometric accuracy and shrinkage, or deconsolidation and void content, the variety still shows the many different perspectives and considerations necessary to assess FRP ISF results. The broader number of failure criteria seen in the reviews of Liu et al. [8] and Hussain et al. [9] is confirmed by the quantitative analysis. Tearing, maximum forming depth, maximum wall angle, wrinkling, deconsolidation, delamination, and bulging have all been studied to assess formability. Other targets studied are also found in conventional ISF, such as the geometric accuracy, surface quality, thickness distribution, forming force, and mechanical strength. However, there are also targets such as edge pull-in, shear, shrinkage, and void content that are less commonly investigated in other material classes.

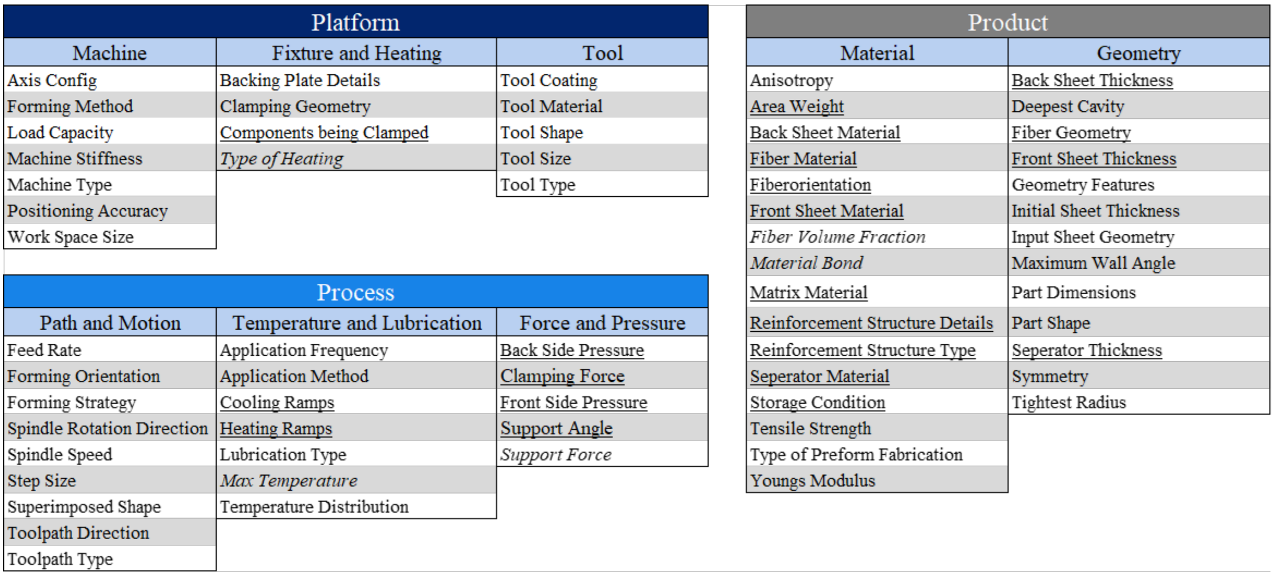
Classification for FRP ISF

Parameters.

Table *1* serves as a reference for the synthesis of the final parameter list. To generate a unified parameter classification for FRP ISF, the 49 unique parameters synthesized from the overview analysis serve as the basis. Next, the total of 20 new parameters derived from the FRP ISF literature are unified with the previous 49. In doing so, the terms Reinforcement Weight Fraction, Forming Temperature, Forming Force, Heat Source, and Material State are replaced by wording better suited in the context of FRP ISF and the rest of the parameter space. Furthermore, Layer Arrangement, Forming Side, Material Type, and Sheet Material are removed by dissolving them into more complex parameter combinations, e.g., by explicitly describing each layer and its side. The unification results in a total of 66 parameters. The new parameters reflect the insights that temperature-related parameters have a crucial influence on the process. They therefore require a more nuanced description in FRP ISF. Due to the more complex material systems employed, product-related parameters become more diverse. The listing of these is often incomplete in existing literature, making interpretation and reproduction difficult. The fiber structure becomes another decisive factor influencing the entire process setup. To emphasize this, it is represented with the parameters Reinforcement Structure Type and Reinforcement Structure Details within the developed classification. The latter is intentionally kept quite general, as there is not yet enough literature to gauge all possibly important parameters of the fiber structure. However, it should be expanded in practice to include as many characteristics of the specific fiber structure under investigation as possible. Examples might be the weave pattern or the initial fabric thickness before blank consolidation.

To sort the parameters into a meaningful classification, an approach with three main categories, similar to those discussed with the classifications of Bremen et al. [10] and Vanhulst et al. [5], is adopted. However, to enable simple expandability and to ensure that all leaves share the same specificity, a consistent three-level system is introduced, structuring the taxonomy into domains, classes, and parameters. The final classification is illustrated in Table *4*. The 66 parameters are grouped into eight classes, organized into three domains. The three domains are Platform, Product, and Process.

Table 4. Parameter classification for FRP ISF (added parameters underscored, renamed once italic).



Platform		
Machine	Fixture and Heating	Tool
Axis Config	Backing Plate Details	Tool Coating
Forming Method	Clamping Geometry	Tool Material
Load Capacity	Components being Clamped	Tool Shape
Machine Stiffness	*Type of Heating*	Tool Size
Machine Type		Tool Type
Positioning Accuracy		
Work Space Size		

Process		
Path and Motion	Temperature and Lubrication	Force and Pressure
Feed Rate	Application Frequency	Back Side Pressure
Forming Orientation	Application Method	Clamping Force
Forming Strategy	Cooling Ramps	Front Side Pressure
Spindle Rotation Direction	Heating Ramps	Support Angle
Spindle Speed	Lubrication Type	*Support Force*
Step Size	*Max Temperature*	
Superimposed Shape	Temperature Distribution	
Toolpath Direction		
Toolpath Type		

Product	
Material	Geometry
Anisotropy	Back Sheet Thickness
Area Weight	Deepest Cavity
Back Sheet Material	Fiber Geometry
Fiber Material	Front Sheet Thickness
Fiberorientation	Geometry Features
Front Sheet Material	Initial Sheet Thickness
Fiber Volume Fraction	Input Sheet Geometry
Material Bond	Maximum Wall Angle
Matrix Material	Part Dimensions
Reinforcement Structure Details	Part Shape
Reinforcement Structure Type	Seperator Thickness
Seperator Material	Symmetry
Storage Condition	Tightest Radius
Tensile Strength	
Type of Preform Fabrication	
Youngs Modulus	

The platform domain groups the mostly constant physical properties of the solution. It contains anything that can be observed without a process running. Its parameters are the most difficult to standardize because changing them requires fundamental physical adjustments of the solution, though to varying degrees. For example, changing tooling might be more feasible than changing the machine type or stiffness. As a consequence, they stay mostly constant within individual research but differ heavily between research groups. The product domain addresses the input and output of the process. Both the initial and target properties of the workpiece are grouped here. With its parameters, the generalizability and possible process variance can be investigated. The process domain is the realm of transient properties. It is the leverage that remains once a platform is set up and a product is chosen. The adjustment of these properties, therefore, also does not require material investment, making it easier to reproduce a given parameter set. However, possible strong correlations with parameters of the platform and product still have to be considered in comparative analysis.

The classes of each domain serve as a semantic clustering of the subordinate parameters. They could be viewed as subcomponents of the process or as classes in its solution space. For the Platform domain, the classes Machine, Tool, and a combined class Fixture & Heating System are chosen. The Process domain is subdivided into the three combined classes Path & Motion, Temperature & Lubrication, and Force & Pressure. The Product domain is described by Material and Geometry Parameters. These classes are not necessarily exhaustive, and further sub-classification might be possible, as is already insinuated by the use of combined classes. Still, to ensure an easy-to-expand framework and distinct structure, a class should always cluster parameters that have a high degree of conceptual or effective interconnectedness.

Lastly, the parameters are the leaves of the taxonomy. They describe both quantitative and categorical properties. To avoid bloating of the framework and to keep it sufficiently general, some parameters in the current formulation might require multiple values to describe them. E.g., the Tool Size of a flat-head tool would require both its major and minor radii. The Part Dimensions parameter might even include three values, one for each spatial dimension. In this regard, this "value components" layer could be considered a fourth level of the taxonomy. Alternatively, each value component could be treated as a separate parameter, thereby dissolving the more general parameters into their subcomponents.

The significant shift in the importance of the domains and classes between conventional and FRP ISF is now also evident in the final framework. In particular, temperature and material parameters are less prevalent in the existing overviews, with only six Product-related parameters occurring in more than one framework and only two belonging to the Temperature & Lubrication class in the Process domain. Their strong influence in the incremental forming of FRP and the more complex material compositions requires a much more nuanced description of these parameters. The final framework contains 7 Temperature and Lubrication parameters and a total of 27 parameters in the Product domain, reflecting this shift.

Target Variables.

The target variable space has only been systematized to a limited extent in the existing overview literature. To structure this space, three main categories are chosen based on the targets discussed in the previous sections. The categories chosen here are Primary / Formability targets, Secondary / Quality targets, and Tertiary / Process targets. These three categories group target variables to answer the questions:

- Was the process able to produce the part,
- What part quality could be reached,
- What is the process performance aside from the resulting part

and in turn to achieve the following three goals,

- Enable the process,
- Improve the outcome,
- Improve and understand the process.

The final target classification is shown in Table *5*. It contains all targets identified in the overviews and in the FRP ISF literature, and includes further targets derived from the questions and goals associated with the three categories. Its structure and contents are described in the following.

Concluding from the previous discussion of formability, it is clear that a single formability measure is not a feasible target variable in FRP ISF. In metal ISF, the approach to measure formability through the maximum wall angle is valid due to the assumption of a single dominant failure mode, fracture after necking through material thinning, and a clear relation of the wall angle to the material thinning. However, severe deviations, such as pillowing or corner folds, could also be considered a "failure" of the process. In thermoplastics, where multiple fracture modes and wrinkling are present, a single formability measure becomes less viable. In FRP ISF, this is exacerbated even further.

That is why formability becomes a category rather than a single target. The wall angle is no longer a target either, but instead, it has to be treated as a parameter affecting possibly multiple underlying mechanisms, as can already be seen in multiple FRP ISF studies. The same also applies to other geometric properties currently used as formability measures, like the forming depth. While this viewpoint may merit debate in the conventional ISF context, it is crucial in FRP ISF. Here, formability is not mainly determined by thinning, but rather a combination of multiple failure scenarios, depending heavily on the initial product configuration. The failure criteria most important in FRP ISF can be structured as shown in Fig. *3*. While all formability aspects are relevant to all products to some extent, the product characteristics determine which aspect dominates the formability. Short fiber reinforced polymers seem dominated by tearing and fracture. With continuous fiber reinforced polymers, especially using a quasi-floating fixture, wrinkling dominates the formability limits. With long fiber or non-woven reinforcements, the expansion or deconsolidation becomes increasingly important. Delamination is an additional failure mode that is relevant only in multi-layer structures, particularly in fiber metal laminates.

Table 5. The developed target variable framework for FRP ISF.

Primary / Formability	Secondary / Quality	Tertiary / Process
Tear	Global Geometric Accuracy	Energy Consumption
Wrinkling	Strength	Forming Forces
Deconsolidation	Stiffness	Processing Time
Delamination	Surface Roughness	Material Waste
	Surface Quality	Particle Emissions
Metal Tear	Thickness Distribution	Noise Emissions
Metal Bulging	Local Geometric Deviations	
Metal Corner Folds	Edge Pull In	
Seperator Tear	Shrinkage	
Seperator Wrinkling	Spring Back	
	Shear Distribution	
	Fiber Ondulation	
	Void Area Fraction	
	Boundary Void Area Fraction	
	Fiber Geometry	
	Void Geometry	
	Constituent Distribution	
	Filament Failure	
	Matrix Cracks	

When using dummy sheets and/or separators, the situation is further complicated by the fact that their failure criteria are combined with those of the composite. This adds tearing, pillowing (bulging), corner folds, and separator wrinkling to the list of failure criteria.

All of these combined criteria might be independently affected by different parameters. While certain geometric features will certainly worsen the effects, limiting the assessment to these features as targets obscures the underlying mechanisms and hinders interpretations, comparisons, and optimization. With the more complex failure criteria, formability targets can to an extent be transferred to their associated quality criteria, e.g., the thickness distribution.

While the exact mechanisms are less investigated than for metals and thermoplastics, a possible attempt to view their transition is shown in Fig. *4*. Material tearing could be preceded by a certain thickness distribution, individual filament failure, or matrix cracks. Deconsolidation up to the point at which it is considered a failed part can be assessed from the part's thickness distribution and void area fraction. Parameters affecting wrinkling could be assessed by examining the shear distribution and local geometric deviations. Delamination could be preceded by an increase in the interfacial void area fraction. This is not intended to provide explanations but rather to emphasize that the boundary between a failed part and a bad part, i.e., between assessing formability and assessing quality, is not necessarily precise. This can also be used to assess the effects of parameters on a formability metric by measuring a related quality metric.

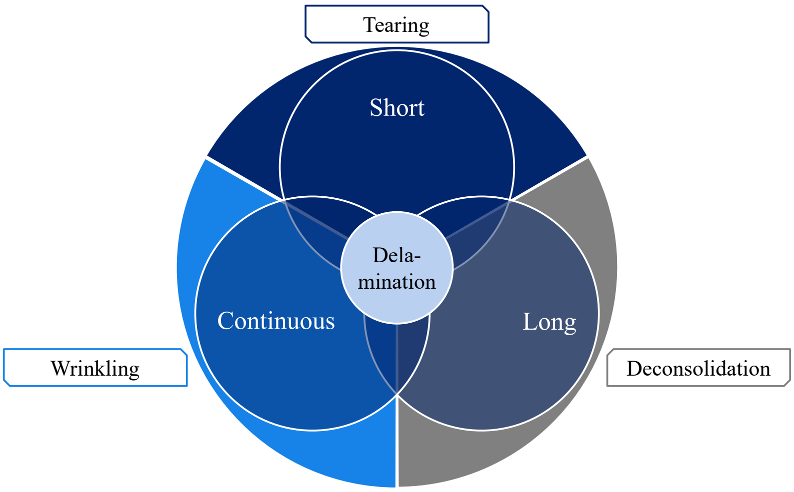


Fig. 3. Failure criteria in FRP ISF and their relation to the reinforcement structure type.

Especially by examining the microstructure of the material, further targets like Fiber Undulation, Fiber- and Void Geometry, and Constituent Distribution can be made available for analysis that may underlay other formability and quality targets. Of course, it is essential to also consider more performance-related quality criteria to assess the process outcome. These are, for example, the Global Geometric Accuracy, Surface Roughness, and Mechanical Strength. They are all collected in the Quality category for now. Further subgroups could be introduced here, such as Mechanical Performance, Geometric Properties, and (Meso)- and Microstructure. Lastly, to further understand the process and, more importantly, to assess and optimize its non-technical performance, the last set of target variables is that which cannot be investigated on the end product. Examples of these targets include Energy Consumption, Forming Forces, Processing Time, Material Waste, and Particle- and Noise Emissions.

As the target space has less existing structure to rely on and differs even more significantly from more common materials, the targets discussed here and listed in Table *5* should even less be assumed to be a complete coverage of the FRP ISF target space. Still, it should serve as a valid starting point for future expansion.

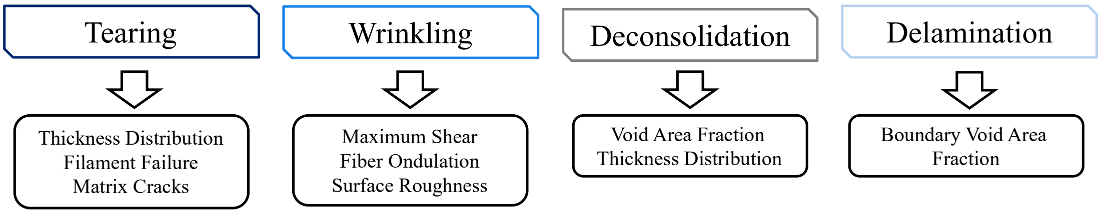


Fig. 4. Possible transition from formability criteria to their related quality metrics.

Notes on Transferability

The taxonomical and structural analysis of the parameter and target spaces is crucial for experiment design and analysis, and can, on its own, already give insights into the transferability and understanding of previous results. For example, using a cone test on a metal sheet and a CFRP layup and measuring the maximum formable wall angle for certain parameter combinations might seem comparable or transferable. Yet explicitly stating the underlying targets reveals a different insight. In the first case, it is the thinning-dependent tear of the sheet, something that occurs in the CFRP only to a very limited extent. In the second case, it might be dominated by shear-dependent wrinkling of the CFRP, which, in contrast, does not typically occur in a metal sheet. Parameters having an identical influence on the thinning of a metal sheet and the wrinkling of a CFRP might exist, but would be a mere coincidence. What appears to measure the same target variable at first glance is, in fact, not.

Examining the relationship between formability and quality criteria also enables more efficient experiment design. It is not necessary to form to failure if it is clear which quality criteria indicate it.

Basic material testing may be important when the translation of material properties into process properties is known.

Lastly, given the vast number of parameters and the absence of standards, it is even more critical to have a comprehensive framework for the documentation of all parameters and factors in any given experiment and a broad recording of target variables to enable transfer between experiments and research groups.

Conclusion

By combining existing classifications with reviews of metal, thermoplastic and composite materials and a systematic review of the FRP ISF literature, comprehensive classifications for the parameter and target spaces of FRP ISF were developed. The parameter classification was structured into three domains and eight subsequent classes that currently cover 65 parameters. The target classification structures 34 corresponding variables into the categories of formability, quality and process.

Large parts of the platform parameter domain were directly derived from existing classifications, whereas the parameter space was significantly expanded in the Temperature & Lubrication and Force & Pressure classes of the Process domain and across the Product domain. Regarding the target variables, it was found that a unified measure of formability is not feasible in FRP ISF. Instead, formability represents a category of separate target variables including multiple failure modes, strongly dependent on reinforcement type and layup configuration. Formability targets can be linked to quality targets, which enables improved experimental design and analysis. To guide a holistic process understanding, the classification also includes performance-related, macroscopic, and microscopic properties. Process related targets complement the formability and quality assessment by facilitating process understanding and assessing its economic and ecological performance.

The classifications are designed to be expandable by additional structure and content as further insights emerge. They can guide the conceptualization and design of experiments as well as the comparative analysis of past and future FRP ISF research and may serve as a starting point for investigations in related material classes.

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