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Work in Progress: Use of Wood-Based Inserts in Injection Molding

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ABSTRACT

In the context of ever-shorter product development cycles and the necessary prototype development, the advantages of the injection molding process cannot be fully exploited because it is not possible to economically produce very small series. The aim of this study is to examine the suitability of soft tooling using wood-based mold inserts for small batch production in polymer injection molding. To this end, various types of wood are being tested in initial injection molding trials as part of this study, and their behavior under the process conditions is being compared. Those wooden molds are milled and tested in various injection molding tests. The produced parts as well as the used molds are then examined for wear, geometric accuracy and in terms of the tensile test specimen, for their load bearing capacity. It was shown that modified materials like laminated wood or compressed bamboo resist the loads of the injection molding process better than natural materials. Also, it was shown that the parts produced have a repeatable geometrical shape. After tool setup, it was possible to produce up to five consecutive workpieces of similar quality. Tensile tests showed reproducible strength values for ABS specimens while wood-fiber reinforced Polypropylene showed unpredictable behavior. Downsides of the new design approach are the longer cycle times which lead to material degradation and the fast wear of the wooden mold inserts.

1 | Introduction

The injection molding process is used in many areas of plastics processing, especially for large batch sizes. The ability to achieve narrow tolerance ranges, high repeatability and reliability, as well as a wide range of usable materials, are just some of the advantages of this manufacturing process. Especially in comparison with the relatively new additive manufacturing processes (AM), which can be used to create much more complex component geometries, the injection molding process is particularly impressive due to its efficiency.

While AM processes are often slow and can only generate one component at a time, injection molding in most cases allows the production of several identical components in one injection molding cycle without increasing the cycle time drastically. Depending on the material, machine size, and component dimensions, these are often only a few minutes or seconds. In AM, producing several identical objects in one process nearly increases the process time linearly. In addition, injection molded components have a lower anisotropy than those generated using a layering process such as 3D printing [1, 2].

However, the market is shifting toward customized products, which has led to lower quantities in tool and mold manufacturing. The economic efficiency of injection molding is limited by the high cost of tooling, which, in some cases, can only be allocated to a small number of components. In addition, the use of injection molding to produce prototypes is not very economical [3, 4]. Each iteration of a product requires either an adjustment of the existing mold or the production of a new injection mold. In contrast, AM does not require any part-specific tooling. Clearly, there is a need for research into more cost-effective injection molding tools or economical process modifications for smaller batch sizes.

1.1 | Rapid Tooling for Injection Molding

In recent years, various efforts have been made to transfer the injection molding process to smaller quantities. For this purpose, a multifunctional basic tool is used into which different mold inserts can be installed. When an AM technique is used to manufacture a tool (e.g., for injection molding) the process is often called rapid tooling. Various materials from AM technology have already been considered as materials for the mold inserts. In their work, Mendible et al. compared mold inserts from conventional manufacturing processes with additively manufactured inserts. The study looked at mold inserts that were either conventionally milled from steel, manufactured from acrylonitrile butadiene styrene (ABS) using the polyjet process or made from bronze using the direct metal laser sintering (DMLS) process. The evaluation of the results shows that the workpieces of the additively manufactured tools have poorer surface quality. The workpieces from the ABS polyjet mold showed increased shrinkage compared to the other processes. The durability of the sintered mold could be proven for 500 cycles, while the ABS mold showed a significantly reduced durability [5].

Harris et al. compared the shrinkage of parts produced in conventional milled aluminum molds with those manufactured in stereolithography (SL) molds. While parts made from ABS encountered almost similar shrinkage effects in both molds, polyamide 66 parts differed much more. As a reason for this effect, the crystallinity of PA66 was identified. Hence, due to the lower heat conduction properties of SL molds, the cooling rate of the part in the SL mold is reduced. Therefore, investigations via differential scanning calorimetry (DSC) showed 30% more crystallinity, which led to more shrinkage and, in total, differed properties of the produced part [6].

Nagahanumaiah et al. were able to show that direct metal laser sintering (DMLS) molds could last at least 5000 injection cycles without showing relevant damages processing Nylon-66. They also were able to show that melt temperature, injection pressure, and injection speed have the highest impact on part shrinkage [7].

Lay et al. compared different additively manufactured injection molds and came to the conclusion that tools made of plastic can be easily used for calibration, prototyping and small series production [8]. Molds produced in the Polyjet process were, due to their high surface quality but their short service life, most suitable for prototyping applications. Molds printed via fused filament fabrication (FFF) from PEEK and 3dkTOP were able to last for more molding cycles. With improved surface quality, these molds were suitable for small-scale production. In a similar approach Kampker et al. analyzed the economic feasibility of additively manufactured injection molding tools [9]. They likewise came to the conclusion that such tools can reduce cost and lead time can be reduced by using AM tools.

In their study, Dizon et al. examined the fit of SLA- and FLM-printed mold inserts in injection molding. In addition to measuring dimensional accuracy, they also investigated the service life of the tools and their failure characteristics. They concluded that FLM-printed mold tools are more prone to tearing than SLA-printed ones due to weak layer bonding. This is also reflected in their service life [10].

Also, other research that investigated the usability and durability of additively manufactured molds came to the conclusion that on some occasions the so-called additive tooling [11] is suitable for prototyping and small batch size processes with low requirements regarding shrinkage and surface properties [12–16]. Kalami and Urbanic focus their research on the overmolding processes of wires [17]. They utilize an additively manufactured sacrificial tool to produce a resin-based mold insert.

For small series, it can be summarized that metallic materials are very cost-intensive and AM plastic mold inserts have a comparatively poor surface quality and low temperature stability. In view of the aforementioned disadvantages of metallic and plastic-based materials, especially for prototype production and small series, and the increasing demands for sustainability and resource conservation, this study examines whether wood or wood-based materials could be a suitable alternative for mold inserts. Wood is readily available, easy to process and, as a renewable raw material, also much more environmentally friendly than the classic mold material steel. For example, the production of 1000 kg of crude steel in a blast furnace releases around 1.744 metric tons of CO_2 [18]. In contrast, 1 metric tonne of wood binds and stores approx. 300 kg of carbon until decomposition or thermal utilization, which corresponds to around 1 metric ton of CO2 [19].

Compared to many thermoplastics, such as ABS, wood is much more temperature-resistant. While the strength of ABS decreases drastically above 100°C (glass transition range 100°C–105°C). Borůvka et al. proved that most of the mechanical properties of birch and beech wood remain largely constant or even increase after heat treatment up to approx. 165°C [20]. It is only beyond this temperature that a decline in mechanical properties occurs.

1.2 | Use of Wood in Tooling

Throughout human history, wood has been used to make tools and devices. Wood is rarely used in modern production processes, but current research is looking into the transfer of wood to modern toolmaking.

Pinto et al. present a modern use case for wooden tools in sheet metal forming. They examined the dimensional accuracy of stamp and die and the effects on the produced part.

They have discovered that both polyurethane-based material and resin-impregnated densified wood have potential as tool materials in small-batch production in metal forming [21].

Geueke et al. also investigated the suitability of wooden tools in sheet metal deep drawing processes. They highlight a fundamental suitability for small-batch production. However, performance depended on the orientation of the wood fibers in the tool [22, 23].

Kriesi et al. present a method for prototyping injection molded parts by using a self-developed desktop-injection molding machine and cheap, easy to proceed mold materials. They also include epoxy impregnated red oak in their study. They point out that the coated wood shows good results as a mold material, but the anisotropy and sensitivity to moisture are disadvantages [24].

1.3 | Conclusion and Research Objective

Since there is no further known scientific literature on the use of wood or wood-like materials for tooling in injection molding, this study was intended to investigate the fundamental suitability of wood-based mold inserts in injection molding technology. As mainstream alternative techniques like Rapid Tooling with plastic AM lack part quality and tool sustainability and wood has the advantage that it can be processed using simple machines, it is of great interest to investigate the suitability of a widely used and readily available material such as wood as a tool material in injection molding. For this, various natural and modified woods and a modified bamboo were analyzed in a single test series. On the basis of the results obtained, initial design guidelines for wood-based molds are to be derived. Systematic investigations of the process and the properties of manufactured components can only be carried out in further follow-up investigations, depending on the achievable scope of the tests. Since these are preliminary tests, a statistical test plan is not used. Rather, these initial investigations are intended to serve as a "proof of concept" and thus form the basis for further investigations.

The overall suitability of various woods as mold materials is evaluated based on injection molding tests with different tools and different plastics under varying process parameters. To assess suitability, the wooden molds are examined for wear and damage after the tests have been completed. The injection-molded parts produced are assessed on the basis of shape accuracy and, in the case of the tensile test rods, their mechanical load-bearing capacity.

2 | Materials and Methods

In order to carry out the desired investigations, several fundamental considerations must be made. These include selecting suitable woods and test specimens, as well as setting up the manufacturing process appropriately.

2.1 | Wood Selection

To ensure that the mold inserts can withstand the high loads during injection molding for as long as possible, a high density was taken into account when selecting the wood and wood-based materials. The mechanical properties of these materials are essentially determined by their density. The higher the density, the higher the strength [25, 26]. For this reason, only wood from deciduous trees, which generally have a higher density than coniferous wood, was considered for the study. Another aspect—particularly against the background of sustainability and responsibility toward nature—was that mainly materials native to Central Europe and readily available woods should be used. Likewise, no precious woods or endangered species were to be used.

Wood consists of three main components: cellulose, hemicellulose, and lignin, which perform different functions within the composite. Cellulose is primarily responsible for tensile strength in the direction of the fibers. Hemicelluloses mainly serve to cross-link cellulose and lignin. Lignin primarily has a supporting function and is therefore able to absorb compressive forces [27]. As wood is an orthotropic material with direction-dependent properties [28] and is comparatively inhomogeneous, wood-based materials were also analyzed. Two of these—birch and beech plywood—have cross-laminated veneer layers, which makes them significantly more homogeneous than the corresponding solid woods.

In order to test the extent to which a highly compressed material has a positive influence on the stability of the mold inserts, a material made of compressed bamboo was also examined. Even though bamboo is not wood from a botanical point of view, but belongs to the sweet grass family and is not native to Europe, it is considered a largely sustainable material with wood-like properties. The manufacturer of the bamboo material is Moso International B.V. The manufacturer does not provide any information about the binding agent. The high-density bamboo material (density of 1.1 g/cm^3 at 12.8% moisture content) is produced by pressing bamboo strips with an adhesive under high temperatures and high pressure.

For ease of reading, the generic term "wood" will be used in the following for all materials used. Based on the selection criteria, the woods listed in Table 1 were analyzed:

TABLE 1 | Overview of considered woods and their used abbreviations.

Wood type	Abbreviation
Birch (*Betula pendula* R.)	BI
Beech (*Fagus sylvatica* L.)	BE
Hornbeam (*Carpinus betulus* L.)	HB
Oak (*Quercus robur* L.)	O
Laminated Birch	LBI
Laminated Beech	LBE
Compressed bamboo (*Bambusoideae* L.)	BA

2.2 | Thermal Properties of Wood

The working temperatures in thermoplastic injection molding range between approximately 180°C and 420°C, depending on the plastic used. It is difficult to estimate the surface temperature of the cavity in the mold, which is why the injection temperatures mentioned above can be used as a first approximation. The glass transition temperature of the wooden components is decisive for mechanical strength at elevated temperatures. Excessive thermal stress causes decomposition (pyrolysis).

Cellulose has a glass transition range between 200° and 250°C in a dry state. The glass transition range of dry hemicellulose is between 150°C and 220°C. The glass transition temperature of lignin in a dry state is specified as up to 205°C [29]. It should be noted that the glass transition ranges in wood are highly dependent on moisture and decrease significantly with increasing moisture [30, 31] When using wooden tools in injection molding, a rapid reduction in surface moisture can be expected due to process-typical conditions in the form of locally acting temperatures significantly above 100°C. As a result, the hygrothermal conditions of the wooden tool approach those of largely dry wood, so that the temperature ranges relevant to the glass transition of the amorphous wood components are presumably only slightly lower than the values specified in the literature for the dry state, especially near the surface.

The thermal decomposition of wood is known as pyrolysis. This is a multi-stage irreversible reaction in which, particularly at temperatures between 200°C and 300°C, the polymer components are thermally degraded, leading to the release of volatile substances. Thermal degradation causes the formation of tar and carbon, leading to a change in color. The bond cleavage associated with pyrolysis, which correlates with mass loss, is the cause of reduced strength [32, 33]. Pyrolysis is influenced by various process parameters and material properties. In addition to temperature and duration of exposure, these include the heating rate, particle size, thermal conductivity, density, heat capacity, and moisture content [34].

Compared to conventional metallic tool materials, wood has a lower density and thermal conductivity. For example, Beech has a density of around 650 kg/m^3, a heat capacity of around 1200 J/kgK, and a thermal conduction ranging from 0.125 up to 0.5 W/mK [35]. In comparison, steel has a density of around 7800 kg/m^3 and thermal conductivity ranging between 14 and 60 W/mK. Aluminum even has a higher thermal conductivity [36]. In addition, the thermal properties of wood are dependent on moisture and direction [35]. So, the cooling potential of wooden mold inserts is expected to be lower than that of conventional materials. The values are also shown in Table A4.

2.3 | Mold Design and Fabrication

Before further processing, the wood was conditioned at 20°C and 65% relative humidity. As a result, the wood moisture content and density were determined. The density was determined in accordance with DIN 52182. The wood moisture content was determined in accordance with DIN EN 13183-1. The results for moisture content and density are listed in Table A1.

For the initial examinations, mold inserts were developed for two different test specimens. The first one is a tensile test specimen based on type 1B of DIN EN ISO 527-2 standards. The external dimensions of the mold inserts for the tensile test specimens were each $95 \times 38 \times 198$ mm^3 (radial × tangential × longitudinal). This specimen can be used to perform tensile tests and to measure the components' dimensions easily.

The second specimen is a round-symmetrical button with a diameter of 37 mm and a thickness of 10 mm. The external dimensions of the mold inserts for the round symmetrical buttons were each $80 \times 80 \times 31$ mm^3 (radial × tangential × longitudinal). To check whether fine details can be produced, this contour has added engraved lettering. Another distinction between the two specimens lies in the design of the sprue. For the tensile test specimen, a runner is employed to create a film gate on one clamping surface. In contrast, the round symmetrical logo is filled directly through the central sprue bushing. The mold filling can therefore be investigated with flow paths of different lengths in the two specimen types.

The cavity of the mold inserts is produced through a milling process. No finishing (grinding) or additional coating was used in this study. While designing the molds, a pronounced demolding slope of 5° and an increased number of ejectors were taken into account. The ejector system is made of steel. To minimize stress on the wood at the injection point, an ejector pin is always positioned there. This means that the hot plastic melt first hits a steel surface. This is based on findings from previous practical trials, which resulted in poor demolding behavior.

Figure 1 shows exemplary the mold inserts for the different specimen types. The tensile test specimen mold is made from hornbeam, while the mold for the button specimen is fabricated from compressed bamboo.

The logo mold insert made of oak already showed severe cracks after production, which is why it was excluded from further consideration. The laminated wood was also only used for the production of tensile test molds. Therefore, only tools made from beech, birch, hornbeam, and compressed bamboo are listed for the logo specimen. Table 2 gives a short overview of the molds used for the tests.

FIGURE 1 | Inserts for different specimen types. Left: Insert for tensile test specimen made from Hornbeam. Right: Insert for Logo-Specimen made from compressed bamboo.

TABLE 2 | Considered materials and specimen type.

Wood type	Tensile test specimen (T)	Logo specimen (L)
Beech	X	X
Birch	X	X
Hornbeam	X	X
Laminated Beech	X	—
Laminated Birch	X	—
Oak	X	—
Compressed Bamboo	X	X

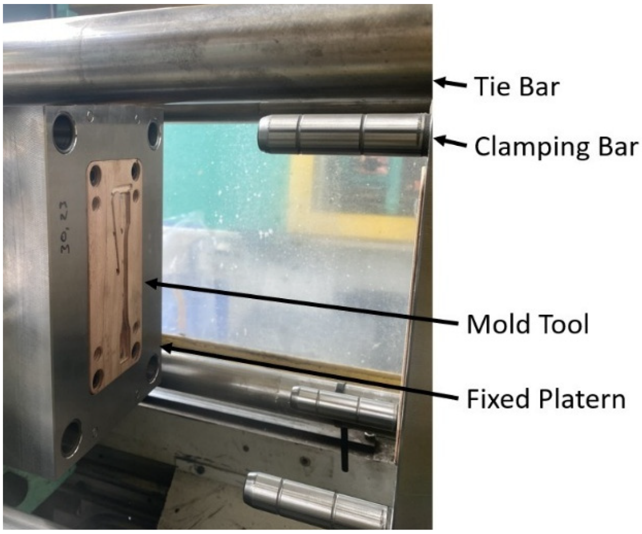

FIGURE 2 | Mounted tensile test mold tool in the ARBURG ALLROUNDER 270C 500–100 with the most important components.

2.4 | Injection Molding Process and Materials

All injection molding tests were carried out on an ARBURG ALLROUNDER 270C 500–100. Two clamping tools were used for the universal mount of the mold inserts. Four different plastics with different material properties and processing parameters were examined. For lower temperatures a wood fiber-reinforced bio-PP was used. An ABS is used for the medium temperature range and a PEEK for mapping high-temperature processes. The unmodified PP showed such strong adhesion in the first tests that it was excluded from further consideration. It still appears in the data listed for the test series in the appendix. The ABS used was Terluran GP-22—ABS from INEOS Styrolution Europe GmbH. The second plastic chosen was a Victrex PEEK (polyether ether ketone) to investigate the processing of a high-performance polymer with significantly higher injection molding temperatures. The third material, the natural fiber-reinforced polymer UPM Formi SPB 30, a Bio-PP (polypropylene), is to be investigated as a sustainable alternative in the injection molding process.

All materials were dried before use. A conventional mold release agent was used before the first cycle to increase demold capability compared to the preliminary tests. The ejector side of an assembled mold for the tensile test specimen is shown in the Figure 2.

FIGURE 3 | Molded parts. Top: Tensile test specimen made of ABS in bamboo mold (T_BA_ABS_2), Bottom: Logo specimen made of PEEK in birch mold (L_BI_PEEK_1).

The different mold inserts were inserted one after the other on the injection molding machine. The choice of process parameters was initially based on empirical values from conventional injection molding processes and preliminary tests that are not presented in this study. Overall, all tests started with lowered injection and holding pressure. They were raised stepwise until complete mold filling or failure (Figure 5). After reaching complete filling, the pressure values were held constant while the cooling time was lowered stepwise. The range of process parameters selected for each mold and plastic can be seen in Table A2.

Figure 3 shows some of the produced parts. The tensile test specimen on top was made of ABS in a bamboo mold and the PEEK logo was molded in a birch mold.

2.5 | Characterization of Failures

To classify the failure patterns occurring while testing a characterization of different defects need to be done. Since the damage on wooden mold inserts cannot be compared to that of conventional injection molding tools, alternative tooling concepts are used as a reference here. Various scientific papers dealing with rapid tooling in injection molding are used for this purpose. Bagalkot et al. analyzed the main failure modes of additive manufactured molds in injection molding. They explain that the mechanical stresses remain constant over several injection cycles and that the damage is therefore attributable to a change in the material behavior of the tool. In addition, high surface roughness has a negative effect on tool durability. They represent signs of wear such as eroded material, thermal decomposition of the tool material, and tears from the mold. They also characterize various types of damage based on mechanical stress, such as shear failure or bending failure. The last type of failure is the tearing of material at the corners of the mold insert [37].

Vieten et al. show the failure evolution process in SLA printed tool-inserts in their work. After incomplete filling of the mold at the beginning of the series they were able to produce some defect-free parts. They point out flash, prolonged dwell time of the material in the injection unit, chipped-off material, and broken parts of the tool as failures [38]. Most of these failure characteristics can be applied directly to the considered use case. Since no study on failure mechanisms of wood-based injection molds could be found, the methods and criteria of BAGALKOT et al. and Vieten et al. are used as a guide for the failure methods employed in this work.

3 | Results

In order to be able to evaluate the tests carried out, failure criteria for the molds were established in advance. If at least one of these failure criteria is met, the test series with the corresponding mold is aborted. These termination criteria for the tests were, firstly, the complete mechanical destruction of the insert, which occurred in the form of cracks or large tears in the surface (Figure 4b). A second termination criterion is the formation of pronounced webbing due to breakouts in the mold, which cannot be removed by simple manual reworking (Figure 4d). Excessive damage to the surface of the cavity was also evaluated as a termination criterion. This occurred either after repeated slight tearing or due to high stress on the mold inserts during the processing of PEEK (Figure 4a). The mentioned failure criteria in the mold and at the produced part can be seen in Figure 4. Smaller tears that do not significantly affect the contour as well as easily removable or small floating skin (Figure 5, picture 3 and 4) were tolerated in this study and did not lead to a test stop with the corresponding tool.

This resulted in only short lifetimes for some of the wooden injection molds, so that not all of the above-mentioned materials could sufficiently be tested in all molds. Some of the molds failed early in testing, that only a small number or even no parts could be produced with them. These parts were excluded from the systematic evaluation due to their poor performance and defined as unsuitable. The wear phenomena and failure criteria that occurred were nevertheless used to identify challenges in the process and to develop design guidelines for the tools.

Some of these tests were carried out with PEEK. The main objective was to examine to what extent wooden molding tools are also suitable for processing high-temperature plastics such as PEEK. For this reason, the tolerance for mechanical damage to the molds or the formation of webbing was greater with these tools. Instead, the test series was aborted if significant thermal damage to the mold was detected, which was indicated by pyrolysis of the surface.

The Tables 3 and 4 show the duration of different tools that were used for the injection molding process. The wooden tools were used until a mentioned termination criterion was met. Subsequently, some of the tools were used in multiple tests with different plastics. The subsequent tests with another material were then aborted when major damage occurred.

Table 3 shows that the tools made from Oak and Laminated Beech when used with PEEK did not perform well with the tensile test specimen. The three tools used showed clear signs of damage right after the first use and were completely damaged after just a minor number of cycles. Only the molds made of hornbeam, laminated beech and bamboo were able to withstand 5 or more injection molding cycles. In addition, only in the test series with Laminated Beech and Bamboo it was possible to produce several consecutive, evaluable tensile test bars. The test series in Hornbeam molds produced only one consecutive evaluable specimen (Figure 5).

Figure 5 shows the evaluation of molded parts in the hornbeam mold (T_HB_1 to T_HB_6). It is clear that the first two cycles did not inject enough material or used too low injection pressure to completely fill the cavity. For this reason, the injection

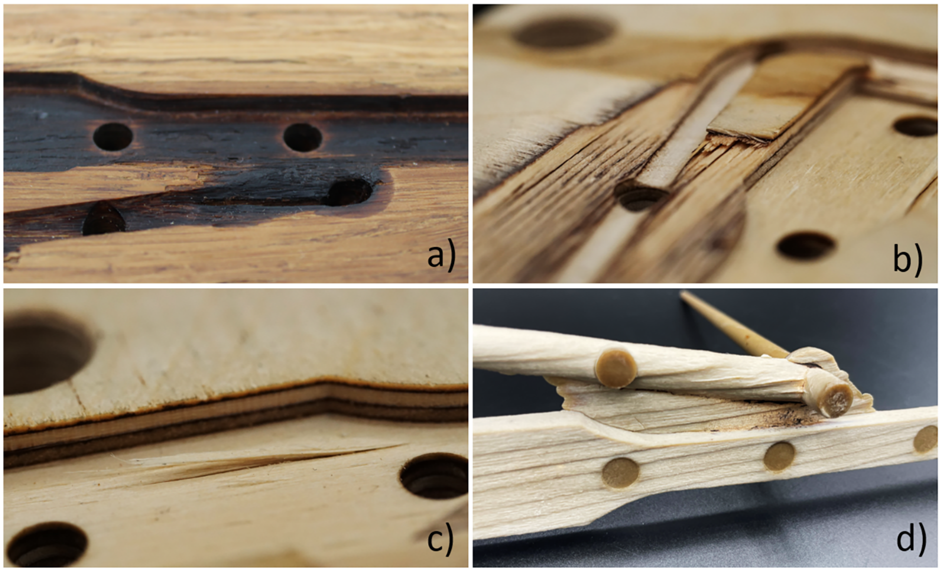

FIGURE 4 | Different termination criteria visualized. (a) Pyrolysis of bamboo-mold-surface, (b) Torn out layers of wood around the sprue and runner. (c) Crack in the laminated mold. (d) Built-Up Floating Skin on produced Tension-Test-Rod. For Scale: Ejector-Pin diameter = 6 mm.

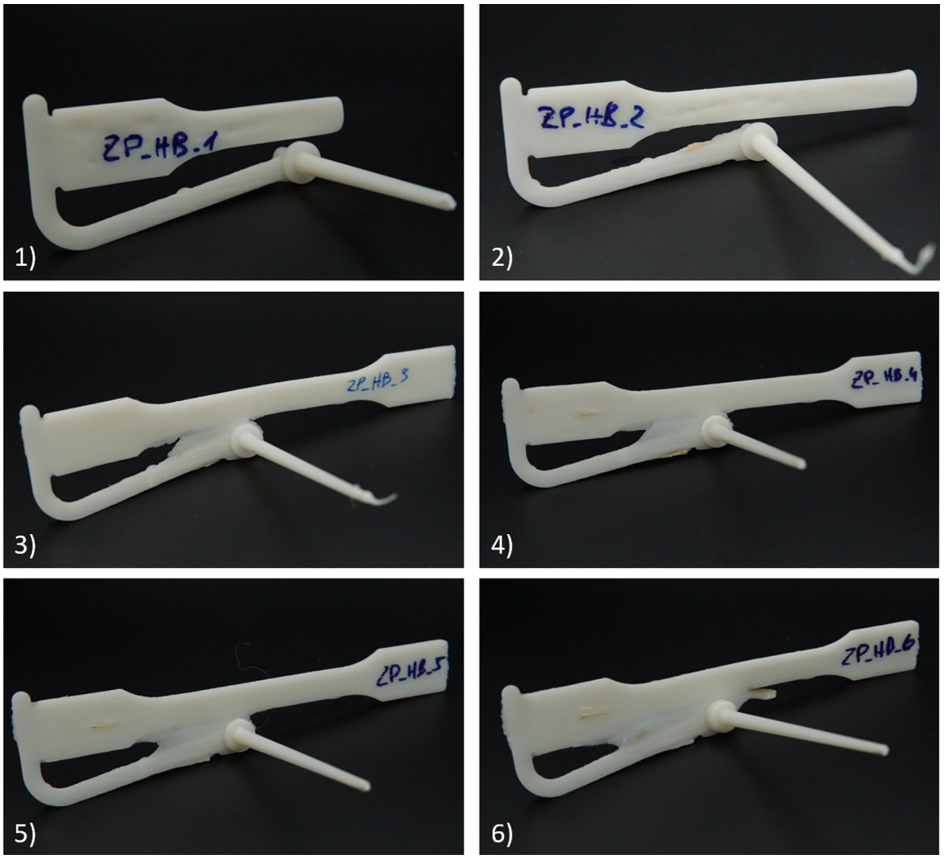

FIGURE 5 | Progress of produced parts in hornbeam-molds.

TABLE 3 | Plastics and number of injection molding cycles performed by the wooden tools with tensile test specimen (T) until termination.

Wood	Plastic	Molding cycles	Consecutive evaluable-parts
Birch	PEEK	6	0
Beech	PEEK	7	0
Oak	ABS	2	0
Hornbeam	ABS	6	1
LBE	UPM	10	5
LBE	PEEK	2	0
LBI	ABS	3	1
Bamboo	ABS	6	6

pressure was increased successively until the complete cavity was filled with plastic in the third shot. From the third shot onwards, rip-outs in the mold resulted in a build-up of floating skin. The floating skin between the runner and the parallel tensile test specimen area grows with every shot. Additionally, splinters from the mold become embedded in the test specimen, indicating further damage to the mold.

Looking at the logo specimen molds, the hornbeam parts cannot be examined correctly. Due to too high set clamping forces, the mold as well as the produced parts were compressed by 2 mm in the closing direction. Only the test series with birch, beech and bamboo can therefore be evaluated.

TABLE 4 | Plastics and number of injection molding cycles performed by the wooden tools with logo specimen (L) until termination.

Wood	Plastic	Molding cycles
Birch	UPM/PEEK	6/4
Beech	ABS	10
Hornbeam	ABS	3
Bamboo	ABS/PEEK	6/6

Therefore, only in the named test series it is possible to examine the manufactured samples for their dimensional accuracy and, in the case of tension rods, for their mechanical properties. A statistically sound evaluation of the results and a detailed comparison of the different types of wood is not possible with the tests carried out. However, all test series can be used to assess the general suitability of the respective wood for injection molding applications by examining the tools and analyzing the damage patterns in combination with the process parameters used.

3.1 | Examination on the Wooden Molds

Investigations of the wood-based injection molds show that the laminated woods sometimes tend to tear between the glued layers. This fact can be attributed to structural defects

TABLE 5 | Geometric measurements at the different measuring spots (MS) of various specimen tensile-test specimens.

ID	Plastic	MS1	MS2	MS3	MS4	MS5	MS6
Nominal value	**—**	**20.76**	**20.76**	**10.76**	**4**	**4**	**4**
T_BA_2	ABS	20.57	20.51	10.62	3.86	3.85	3.9
T_BA_3	ABS	20.57	20.58	10.7	3.87	3.89	3.9
T_BA_4	ABS	20.58	20.61	10.72	3.88	3.92	3.91
T_BA_5	ABS	20.60	20.57	10.66	3.92	3.94	3.93
T_BA_6	ABS	20.58	20.57	10.65	4	3.96	3.97
T_LBE_4	UPM	20.58	20.42	10.58	3.88	3.91	3.86
T_LBE_5	UPM	20.66	20.47	10.66	3.89	3.9	3.89
T_LBE_6	UPM	20.66	20.57	10.72	3.91	3.86	3.89
T_LBE_7	UPM	20.56	20.59	10.78	3.96	3.91	3.92
T_LBE_8	UPM	20.58	20.62	10.8	4.02	3.97	3.99
T_LBE_9	UPM	20.49	20.57	10.69	4.06	3.93	3.98
T_HB_3	ABS	20.46	20.63	10.69	4.03	4.06	3.94
T_HB_4	ABS	20.56	20.69	10.7	4.03	4.08	3.92
T_HB_5	ABS	20.56	20.8	10.76	3.97	4	3.85

characterized by air inclusions within the adhesive bond. Regardless of the orientation of the individual layers of the material, pressure forces always also occur in a direction transverse to the direction of the layers in the injection molding process. Consequently, delamination and destruction of the mold cannot be ruled out. The other woods all showed signs of wear as a result of the high forces and the adhesive plastic melt flowing past them. Over time, individual wood fibers became detached from the surface of all the molds used. This primarily led to a poorer surface quality of the injection-molded components produced. At the same time, the resulting grooves/trenches in the mold represent a weakening of the material, so that damage patterns often spread from these defects with repeated use.

The molds made of compressed bamboo were the least affected by this damage pattern. Due to the high density and impregnation of the material with binder, fewer fibers were detached from the wood.

A further pattern of damage to the molds was found particularly during the processing of PEEK, but also when the mold was used repeatedly in short cycles: pyrolysis of the mold surface. This indicates excessive thermal stress on the mold and leads to a weakening of the mold. The formation of cracks in the mold shows that the wooden molds were used close to or even beyond their load bearing limit at the selected process forces.

3.2 | Geometric Repeatability of the Molded Parts

To evaluate the repeatability of the process in terms of dimensional accuracy of the produced workpieces, the samples are measured manually using calipers. Only sample series that allow measurements on at least three consecutive molded parts are considered. Some of the test specimens have minor floating skin, which was not removed for the dimensional measurements. Only samples where the protrusions did not affect the measured values are taken into account. This approach allows the measurement of five consecutive samples from the mold made of compressed bamboo, six samples from the mold made of laminated beech as well as three specimens made in hornbeam. Table 5 shows the measured values at the different measuring points for the samples BA2 … BA6, LBE4 … LBE9 and HB3 … HB5. In addition, Figure 6 shows the different measuring spots (MS) on the tensile specimen. The overall length of the specimens was not taken into account, because the film gate is located on one of the contact surfaces for the caliper. Due to the manual removal of the gate, no reliable statement is possible as to whether the measured total length is due to the injection molding process or the post-processing.

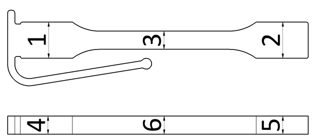

FIGURE 6 | Visualization of the different measuring spots on the tensile test specimen.

The recorded values per sample and the averaged standard deviation of the different sample groups at the individual measuring spots are listed in Table 5 and Figure 7.

When examining the measured values, the measurement inaccuracy that arises when working with a caliper should also be taken into account. Besides the accuracy of the measuring device itself, measuring errors caused by the user (e.g., wrong alignment, measuring on small floating skins or missing parts) also affect the results. Another influencing factor is the surface roughness of the molded parts, caused by the structuring of the wooden mold.

Comparing the standard deviation of the values measured at different points on the sample with the values specified in DIN

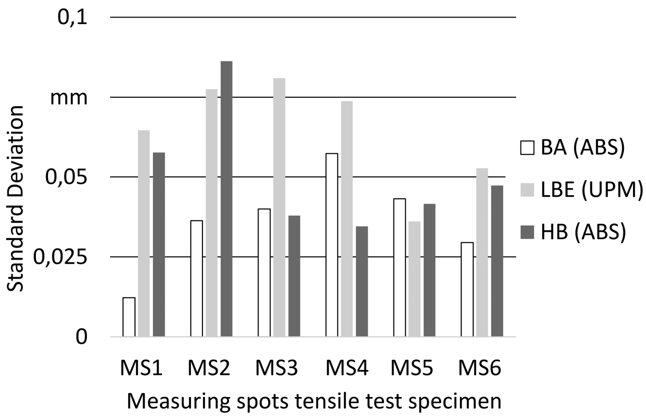

FIGURE 7 | Comparison of the standard deviation of taken measurements at different measuring spots of tensile test specimen in mm.

ISO 20457 for achieving different degrees of tolerance in injection molding, the manufactured parts can be evaluated in terms of their dimensional accuracy within a standardized framework. It is noticeable that the tolerance grade TG5 is achieved in the worst case. In most cases, the tolerance fields of TG3 or TG4 are achieved; in exceptional cases, even TG1 and TG2 were noticed.

These tolerance classes correspond to a medium to fine tolerance in injection molding. It can therefore be seen that the tensile test bars produced in the above-mentioned wooden molds meet the usual accuracies in injection molding. However, it must always be taken into account that the necessary tolerances in injection molding are specified by the customer. If the customer specifies a finer tolerance class in his catalog of requirements, this cannot be achieved with the injection molds made of wood. However, since the innovative tools investigated here are not intended for mass production of pristine components, but rather for small series and prototypes, fine tolerance requirements may not be usual. The tolerances determined can be seen as a positive result.

The round button samples, shown in Figure 8, were measured in a manner consistent with the tensile test rods. Parts with excessively large floating skins or defects due to insufficient mold filling were not included in the evaluation.

The measurements that can be taken with the caliper are the thickness of the button and the diameter at three different points, each offset by 60° (Figure 8). The mean value and the standard deviation of the three measured diameter values can be used to determine the general shape deviation of each button compared to the target value.

Table 6 shows the results for the Button-Specimen. The averaged values with their standard deviation are also shown in Figure 9. With the logo-cavity, there are also significant variations in the durability of the mold inserts. Again, the compressed bamboo shows the best durability as well as an insert made from birch. These test series also show a similar picture to the tensile test bars in terms of the tolerance levels achieved. In the worst case, a tolerance level of TG5 is achieved. Most of the dimensions are in the tolerance classes TG2 to TG4. For the ABS samples produced in bamboo, the best tolerance class TG1 is even achieved

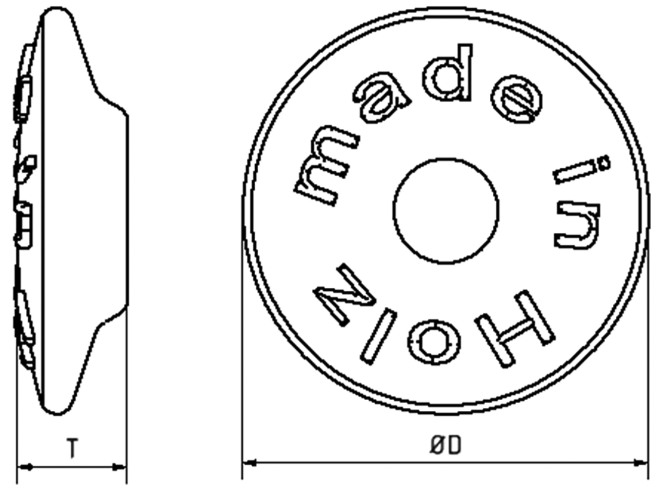

FIGURE 8 | Different measuring spots on the logo specimen. Diameter is measured three times on each mold, thickness once.

TABLE 6 | Mean measurements and standard-deviation of the logo-specimen in [mm].

ID	D1 [mm]	D2 [mm]	D3 [mm]	T [mm]
Nominal value	**37**	**37**	**37**	**10**
L_BI_PEEK_1	36.95	36.68	36.34	10.16
L_BI_PEEK_2	36.92	36.85	36.41	10.04
L_BI_PEEK_3	36.37	36.91	36.56	10.27
L_BI_PEEK_4	37.08	36.46	36.52	10.32
L_BI_UPM_1	37	36.83	36.56	10.03
L_BI_UPM_2	36.85	36.87	36.7	9.98
L_BI_UPM_3	36.92	36.64	36.66	9.86
L_BI_UPM_4	36.88	36.8	36.86	9.92
L_BI_UPM_5	36.81	36.76	36.83	9.85
L_BI_UPM_6	36.88	36.42	36.52	9.96
L_BE_ABS_5	36.6	36.63	36.62	10.16
L_BE_ABS_6	36.75	36.67	36.63	10.03
L_BE_ABS_7	37.12	37.28	37.04	10.15
L_BE_ABS_8	36.85	36.56	36.53	10.37
L_BE_ABS_9	36.7	36.68	36.72	10.38
L_BE_ABS_10	36.92	36.36	36.71	10.28
L_BA_PEEK_1	36.56	36.6	36.61	9.79
L_BA_PEEK_2	36.67	37.73	36.65	9.82
L_BA_PEEK_3	36.83	36.8	36.71	9.94
L_BA_PEEK_4	37.3	36.98	36.88	10.12
L_BA_PEEK_5	37.33	36.85	36.96	10.14
L_BA_PEEK_6	37.31	36.88	36.96	10
L_BA_ABS_1	36.86	36.82	36.77	10.12
L_BA_ABS_2	36.8	36.87	36.84	10.02
L_BA_ABS_3	36.86	36.9	36.85	10.06
L_BA_ABS_4	36.85	36.8	36.77	10.04
L_BA_ABS_5	36.73	37.01	36.66	10.03

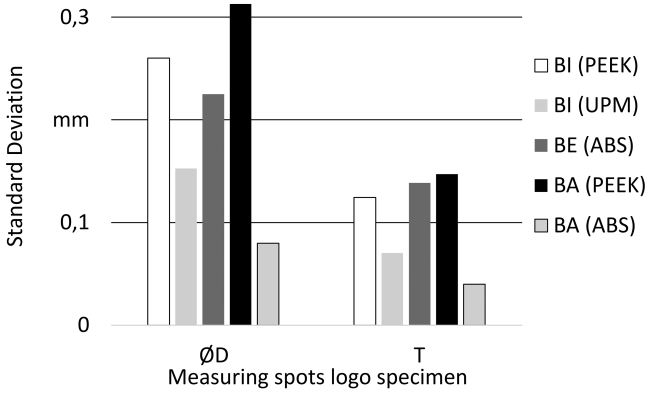

FIGURE 9 | Standard deviation of the diameter (D) and thickness (T) of the logo specimen in mm.

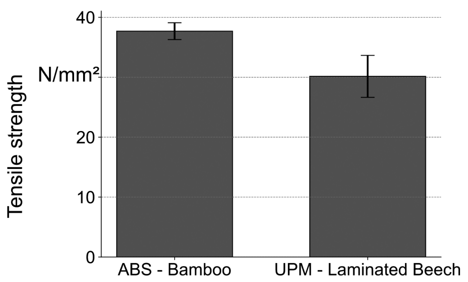

FIGURE 10 | Force-Strain Diagram of the five ABS specimens produced in Bamboo mold.

for both the tool-related dimensions (diameter D1–D3) and the non-tool-related dimensions (thickness T).

3.3 | Examination of Mechanical Properties

In order to obtain an impression of the mechanical properties of the samples produced, a number of selected samples are tested for their tensile properties on a Galdabini Quasar 25 universal testing machine. All stresses listed are calculated with the ideal sample cross-section of 41.61 mm^2, according to the CAD model of the test rod. As already described, some of the samples had webbing between the sprue and cavity. These were removed manually before mechanical testing.

The specimens for the tensile tests are divided into two test series, each consisting of five specimens. The first one contains the specimen T_BA_ABS_2 up to T_BA_ABS_6. They were produced in the mold made from compressed bamboo. The samples in the series were produced sequentially in the inserts to ensure optimal geometric reproducibility. To continuously optimize the process despite the low number of shots, various process parameters were varied between the trials of each series. The process parameters for each shot can be taken from Table A3. Nevertheless, the results provide an initial impression of the mechanical properties as well as the reproducibility of the process. The strength results of the tests are shown in Figure 10.

The first series made of ABS plastic shows consistent results in terms of strength (Figure 10). The tensile strengths are ranging between 35.5 and 39.1 N/mm^2. Apart from sample T_BA_ABS_2, which was manufactured with a lower holding pressure, the values are at a similar level in terms of the tensile strength, which is shown in the low standard deviation of 1.4 N/mm^2. However, the elongation at break of the samples fluctuates greatly, with sample T_BA_ABS_6 with the highest tensile strength also having the highest elongation at break, which is more than three times higher than the elongation at break of sample T_BA_ABS_4. Overall, the elongation at break scatters more than the strength values.

FIGURE 11 | Cut out part from a reference sheet (bottom) and a molded logo specimen from UPM (L_BI_UPM_4) with visible discoloration.

The second series of specimens are made of wood fiber-reinforced polypropylene and shows less reproducible force values. The fracture behavior of the samples is very brittle and both the strength and the elongation at break are subject to great fluctuation. The tensile strength values are between 25.4 N/mm^2 (T_LBE_UPM_5) and 35.6 N/mm^2 (T_LBE_UPM_9). The inconsistent strength values result in a higher standard deviation of 3.5 N/mm^2. A striking feature of the samples made of fiber-reinforced polypropylene is that the color of the molded components differs from that of the granules or conventionally manufactured molded parts. There is a brown-yellow discoloration of the material which can be seen in the Figure 11. The cut-out part from a reference sheet is brighter than the specimen L_BI_UPM_4.

4 | Discussion

Although the small sample size does not allow the results obtained to be statistically reliable, it can still be deduced from the tests that injection molds made of woods allow components to be manufactured in a repeatable, true-to-shape manner. It is noticeable that for both sample geometries, the production of ABS parts in bamboo molds achieves the best reproducibility in terms of mold fidelity. In particular, since the molds used for this purpose also enable the best service life, compressed bamboo currently appears to be the most suitable for the production of injection molds.

The injection molding tests show that there are major differences between the materials under consideration. The unmodified, solid woods exhibit very unpredictable behavior. This can be attributed to the inhomogeneous character of wood. The best results were achieved with compressed bamboo and beech plywood. This is due to the fact that compressing bamboo or cross-laminating and pressing veneers results in a more homogeneous material with improved properties compared to the unprocessed raw wood. In addition, the wood-based materials and the compressed bamboo contain a higher proportion of binding agents, which also improve the mechanical properties.

The mold for the tensile test specimen suggests that specific design rules are necessary for inlets made from softer and less strong materials. Increasing the draft angle and the number of ejectors compared to conventional design rules had a positive effect on demold capability in the tests carried out. The need for larger draft angles and the increased number of ejectors limits the design freedom of the parts produced. It can therefore be assumed that wooden molds are not suitable for the production of every type of prototype. The surface roughness of the wooden mold inserts will be higher than that of conventional metal inserts. In addition, the surface will wear due to small tears. This further impairs the demolding properties. In this study, a conventional mold release agent was used. Further investigations might test more different coatings or surface treatments of the wooden inserts. Coating the surface with synthetic resin could lead to increased tear resistance and thus less wear and improved demoldability.

Frequently, the failure of the tensile test inserts was attributed to a floating skin connecting the inlet to the main cavity. In contrast, fewer instances of floating skins were observed at the end of the flow path or in the logo specimen, caused by lower local pressure. The reason for this is the short distance between the sprue and the main cavity. The wood was not able to seal against the high injection pressure at this location. The logo shows fewer such features, as the sprue is positioned directly in the cavity and therefore less pressure is required to fill the contour. So, another design rule is to use sprue channels that are as short as possible or none at all; ideally, the inlet should be located directly in the component cavity. Another case of failure is the tearing of fibers from the wood surface. This can be due to both the rough surface structure of the wood and the comparatively low shear strength of the wood fibers.

The tests with the PEEK show that the wood-based mold inserts are not suitable for processing high-temperature thermoplastics. The wood surface begins to pyrolyze under the increased thermal load. Pyrolization starts at around 200°C and is a time-dependent effect. The thermal load while processing the lower temperature materials does not cause any visible thermal degradation. Further research might analyze the temperature range between 240°C and 400°C in more detail. Thermal simulations could also assist this research, especially with regard to reducing cycle time.

Process parameters need to be optimized for the new tooling approach. Especially the clamping force and the holding pressure showed influence on the service time of a tool. Setting the values too high deforms the wood or leads to increased tearing. The cooling times are significantly longer with wooden inserts, which is due to the low thermal conductivity of wood compared to metals. The slower heat dissipation not only leads to increased cycle times, but also to a longer thermal load on the mold material. Another effect of the increased cycle times is the longer dwell time of the polymer in the heated extrusion screw, which may cause degradation of the material. This was visible in the discoloration of the wood-fiber reinforced PP material. This may be a reason for the material's low repeatable tensile strength. The tests with ABS showed no such effect. It can therefore also be assumed that the new tools are not suitable for processing all kinds of materials.

5 | Conclusion

In general, the study shows a fundamental suitability of special wood-based materials and compressed bamboo. The results achieved with laminated beech and compressed bamboo are more promising than those obtained with native solid woods. This is primarily due to the modified material properties, as processed woods exhibit reduced anisotropy and lack natural defects such as knots, which can significantly reduce their performance.

The mold inserts are able to produce a small number of components with reproducible dimensional accuracy. Other modified materials that are particularly suitable for use in jig and mold construction can be the subject of further investigation. It is also necessary to further optimize the design of the mold inserts so that there is less floating skin formation and better demold ability. Further research is also required with regard to material tear-out. It is possible to increase the service life by further optimizing the surfaces through fine machining or coating.

Natural woods are only suitable to a limited extent, as the service life of the molds is unpredictable due to random defects in the wood structure. In addition, the low splitting strength parallel to the grain direction is a major problem, which leads to severe tearing.

Plastics with a low to medium processing temperature (ABS and UPM) can be injected into a wooden mold several times without creating thermal defects to the mold. A high temperature plastic such as PEEK causes major pyrolysis in the cavity which leads to weakening of the wooden mold. Therefore, wooden molds seem to be unsuitable for these high-temperature processes. Nonetheless, further investigations on heat distribution and cooling inside the mold can be carried out to increase the performance with low to medium temperature processes and may reduce the cycle time.

Further investigations should also be carried out with a lower number of varying factors, to obtain statistically analyzable and repeatable results. Long-term tests should therefore be carried out on the service life of the inserts under constant process parameters. In addition, the design should be adapted so that there is no systematic defect, such as the floating skin between the sprue and cavity. Furthermore, the choice of materials should be limited to wood-based or wood-like materials with the highest possible density, as these are the most promising. The use of release agents or coatings in the molds should also be investigated in order to increase the service life and component quality.

In conclusion, the presented work provides a comprehensive foundation of knowledge and understanding that will inform future research endeavors in the field of wooden tooling for injection molding.

Author Contributions

David Grundmann: project administration, investigation, writing – original draft, writing – review and editing, visualization, conceptualization, methodology. **Michael Mainz:** writing – review and editing, visualization, writing – original draft, investigation, methodology, conceptualization. **Leo Munier:** writing – review and editing, writing – original draft, investigation, project administration, conceptualization, methodology, visualization. **Fabian Dillenhöfer:** writing – review and editing. **Alexander Pfriem:** writing – review and editing. **Bernd Künne:** writing – review and editing. **Marcel Bartz:** writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

TABLE A1 | Arithmetic mean value of density ($\overline{\sigma}_c$) and moisture content ($\overline{MC}$) with corresponding standard deviation (S_{σ_c}, S_{MC}) for the analyzed woods and wood-based materials after storage at 20°C and 65% relative humidity.

		Birch	Beech	Hornbeam	Oak	Beech plywood	Birch plywood	Compressed bamboo
Density in g/cm^3	$\overline{\sigma}_c$ S_{σ_c}	0.62 0.05	0.63 0.04	0.64 0.01	0.62 0.02	0.77 0.01	0.75 0.01	1.08 0.04
Moisture content in %	$\overline{MC}$ S_{MC}	13.28 0.18	11.88 0.11	15.58 0.14	15.28 0.41	13.28 0.21	14.04 0.12	13.31 0.44

TABLE A2 | Process parameters for the different injection molding processes.

Wood	Specimen type	Plastic	Barrel temperature in °C	Injection pressure in bar	Holding pressure in bar	Holding time in s	Cooling time in s	Clamping force in kN
BI	Tensile	PEEK	360–400	1500–1800	300–400	6	90–120	85
LBE	Tensile	PEEK	360–400	1800	300–400	6	90–120	85
LBE	Tensile	UPM	165–195	700–750	25–250	6	60–90	75–100
LBE	Tensile	ABS	210–240	750–1000	150–400	6	90	100–200
LBI	Tensile	ABS	210–240	750	200–300	6	60–90	100
HB	Tensile	ABS	210–240	750–1000	200–300	6	60–90	50–100
BE	Tensile	ABS	210–240	750–1000	200–400	6	90	75–85
OA	Tensile	ABS	210–240	1000	350–400	6	90	85
BA	Tensile	ABS	210–240	1000	200–450	6	90	85
BA	Tensile	PEEK	360–400	1000–1800	350–450	6	120	85
BE	Tensile	PEEK	360–400	1800	350–450	6	90	85
BA	Logo	ABS	210–240	500	150–200	1–4	180	15
BA	Logo	PP	180–220	500	100–200	4–6	180	15
BA	Logo	PEEK	360–400	1500	150–400	6	140	15
BI	Logo	UPM	165–195	500	140–150	6	120–180	15
BI	Logo	PEEK	360–400	1800	150–450	6	160–180	15
BE	Logo	ABS	210–240	500	50–500	1	60–180	10–15
HB	Logo	ABS	210–240	500	25–200	1	60	50

TABLE A3 | Process parameters of the tensile tested tensile specimen.

Specimen	Injection pressure in bar	Holding pressure in bar	Holding time in s	Cooling time in s	Clamping force in kN
T_BA_ABS_2	1000	300–250–200	6	90	85
T_BA_ABS_3	1000	400–350–300	6	90	85
T_BA_ABS_4	1000	450–400–350	6	90	85
T_BA_ABS_5	1000	450–400–350	6	90	85
T_BA_ABS_6	1000	450–400–350	6	90	85
T_LBE_UPM_5	750	200–150–100	6	90	85
T_LBE_UPM_6	750	250–200–150	6	60	85
T_LBE_UPM_7	750	250–200–150	6	60	100
T_LBE_UPM_8	750	250–200–150	6	45	100
T_LBE_UPM_9	750	250–200–150	6	60	100

TABLE A4 | Physical properties of various mold materials.

	Density in kg/m^3	Thermal conduction in W/mK	Compressive strength in N/mm^2	Tensile strength in N/mm^2
Beech	650 [35]	0.125–0.5 [35]	41–99 [39]	57–180 [39]
Steel	7800–8000 [36]	14–60 [36]	—	310–1850 [36]