

Article

Thermal Degradation and Thermomechanics of Castable Photopolymer Resins After Curing

Anna A. Kamenskikh ^{1,2,*} , Dmitry O. Pustovalov ^{3,4} and Veronika I. Strukova ^{1,2,4}

¹ Department of Computational Mathematics, Mechanics and Biomechanics, Perm National Research Polytechnic University, 614990 Perm, Russia; veloiv_pstu@mail.ru

² Laboratory of Digital Engineering of Mechanical Engineering Processes and Production, Perm National Research Polytechnic University, 614990 Perm, Russia

³ Department of Innovative Technologies in Mechanical Engineering, Perm National Research Polytechnic University, 614990 Perm, Russia; pustovalov.dmitrii@inbox.ru

⁴ Student Design Bureau Technological Mechanics of Additive and Casting Processes, Perm National Research Polytechnic University, 614990 Perm, Russia

* Correspondence: anna_kamenskikh@mail.ru; Tel.: +7-(342)-239-15-64

Abstract

This current work considers six specialized castable photopolymers from different manufacturers that are promising for the formation of a process map for casting using burnt models: Harz Labs Dental Cast Cherry; Gorky Liquid Castable; Gorky Liquid Dental Castable; JAMG HE Ultra Cast UV Resin (90% WAX); JAMG HE Jewelry Casting Resin (25% WAX); Siraya Tech Cast Royal Blue. The additive growth parameters of the structures were selected to provide quality indicators of photopolymer models. Thermogravimetric analysis and dynamic mechanical analysis were chosen as the main methods of experimental analysis. Thermogravimetric analysis was performed at temperatures up to 700 °C. Thermal decomposition of castable photopolymers has several stages of decomposition with different rates of destruction. Gorky Liquid Castable has the fastest thermal decomposition. The material has less than 1% of the residual weight at 530 °C. The minimum ash content is in Siraya Tech Cast Royal Blue (less than 0.1%). Dynamic mechanical analysis was performed at temperatures up to 225 °C for samples grown in different printing directions. The printing direction affects the storage modulus, loss modulus, and tangent of the angle of mechanical losses of photopolymer materials, on average by no more than 35%. Glass transition temperatures of materials and zones of relaxation transitions are established. The glass transition temperatures depend little on the direction of printing of the samples. JAMG HE Ultra Cast UV Resin (90% WAX), a photopolymer with a maximum wax content, has the minimum glass transition temperature of 30–32 °C. JAMG HE Ultra Cast UV Resin (90% WAX) does not have a pronounced relaxation transition zone.

Keywords: photopolymer resin; castable resin; process parameters; additive production; thermophysics; thermomechanics; destruction; ash content; temperature dependencies; storage modulus; loss modulus



Academic Editors: Roberto Bernasconi and Prisca Viviani

Received: 29 June 2026

Revised: 24 July 2026

Accepted: 31 July 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Additive manufacturing (AM) is commonly known as 3D printing. This is a set of technologies for the layer-by-layer creation of three-dimensional objects based on digital models [1]. AM is characterized by almost unlimited freedom of design, significantly reduced consumption of raw materials, and the ability to reproduce geometrically complex

shapes without the use of forming equipment [2]. These are important and basic differences between AM and traditional subtractive methods. Additive technologies are divided into seven basic groups, according to the ISO/ASTM 52900 classification. Vat photopolymerization (VPP), combining methods such as laser stereolithography (SLA), projection digital light processing (DLP), and printing using liquid crystal matrices (LCD), is distinguished separately [3]. The operation of VPP systems is based on the selective curing of a layer of a liquid photosensitive composition under the influence of radiation of a certain spectral range (in most cases, 385–405 nm). DLP provides a higher printing speed compared to SLA due to the possibility of simultaneous curing of the entire layer, while maintaining a high resolution (up to 10–50 μm in the XY plane) [4,5]. LCD technology, being a further development of DLP, offers an even lower cost of equipment with a comparable surface quality [6].

Initially, VPP was used exclusively for rapid prototyping using acrylate resins with limited mechanical properties [7]. Over the past ten years, there has been intensive progress in the creation and production of materials for photopolymer additive printing. High-strength engineering photopolymers, elastomeric compositions, biocompatible hydrogels, and materials filled with ceramic, metal particles, or carbon nanostructures have appeared, along with traditional compositions [8]. The range of applications of VPP technologies has expanded due to this, including functional units of aerospace and automotive engineering [9], biocompatible implants and matrices for tissue engineering [10], microfluidic chips [11], etc. Investment casting is one of the most popular areas. Additively synthesized models made of specialized photopolymer resins replace classic wax blanks. This opens up the possibility of manufacturing casting molds of increased complexity while reducing the production cycle and costs. This solution is especially relevant for dentistry, the jewelry industry, and the aircraft industry.

The effective implementation of investment casting imposes a number of specific requirements on photopolymer materials. These include residual ash content at a level of not more than 1%; the predictable nature of thermal destruction [12,13], which excludes the formation of defects in the casting mold; low thermal shrinkage [14]; and sufficient strength properties of the cured polymer, which guarantee the preservation of the geometry of the model when applying shell mixtures. However, the expansion of the nomenclature of materials is associated with a number of fundamental and applied problems. The addition of fillers leads to scattering and absorption of light, which affects the depth and width of curing and also increases the viscosity of suspensions, making it difficult to recoat [15]. The production of ceramic and metal products with high relative density is associated with the need for multi-stage heat treatment, including the removal of the polymer matrix and subsequent sintering [16]. In the case of castable photopolymers, the key step is precisely the destruction of the polymer binder system, which must occur completely and with a minimum residue. The nature of the decomposition (temperature range, speed, step) directly affects the integrity of the ceramic shell and the quality of the resulting casting.

Despite the growing use of castable photopolymer resins, systematic studies of their thermomechanical behavior and thermal degradation after curing remain fragmentary. Pszczółkowski et al. [17] note the need to study the mechanical properties of cured photopolymer resin. Rudnik et al. [18] note that the mechanical behavior of photopolymer resin structures remains poorly understood. Manufacturers often provide only limited data (for example, the total percentage of ash content at one temperature), but do not disclose the full thermogravimetric (TG) and dynamic mechanical (DMA) characteristics. Moreover, the parameters of additive cultivation (exposure time of the base and working layers, printing orientation), which significantly affect the internal structure, defectiveness, and, as a result, the properties of the finished material, are often recommended by manufacturers without

sufficient justification. As shown in a number of papers [19,20], the optical properties of the resin (the presence of dyes, pigments, fillers) radically change the depth of radiation penetration and the critical energy of polymerization, which requires individual adjustment of printing parameters for each composition. Meanwhile, the effect of these parameters on the subsequent thermomechanical behavior during heating (up to the decomposition temperatures) is practically not studied. There are no comparative data on the viscoelastic properties of castable resins of different manufacturers, on the dependence of the glass transition temperature and storage modulus on the orientation of the layers, or the nature of mass loss in a wide temperature range (from room to 700 °C). Such information is necessary for building correct burnout flow charts, selecting heat treatment modes, and preventing defects such as cracking of the shell, the formation of pores, and carbon residue.

Thus, the purpose of this work is a systematic experimental study of three key aspects of the casting technology using castable photopolymer resins: (1) the selection of rational parameters of layer-by-layer DLP-growth for six commercial resins of Russian and foreign manufacturers, (2) the evaluation of thermal destruction of cured samples by thermogravimetric analysis (TGA) with determination of the temperatures of the beginning of rapid decomposition and residual ash content, and (3) the analysis of thermomechanical properties (storage modulus, loss modulus, mechanical loss angle tangent) by dynamic mechanical analysis (DMA) in the range from 0 to 200 °C, including evaluation of the effect of printing orientation in the Cartesian coordinate system. In addition, for one of the resins, the effect of printing at an angle of 45° was investigated using supporting structures. The obtained data are intended to form the basis for optimizing the process of burning models in the manufacture of high-quality casting molds, as well as to become the basis for digital analogs of materials and stages of the technological process of investment casting.

2. Materials and Methods

The formation of a complete investment casting process flow chart requires additional data on technological parameters, thermophysical, and thermomechanical properties of photopolymer resins:

1. Selection of rational parameters for layer-by-layer growth of photopolymer models, including taking into account thin and curved elements.
2. Assessment of the thermal degradation of photopolymer materials after curing and determination of the residual ash content of the materials.
3. Analysis of the thermomechanical properties of materials within a continuous medium, before significant thermal destruction.
4. Determination of the dependencies of thermal expansion coefficients of photopolymer materials within a continuous medium on temperature.

This article is devoted to the first three areas of research necessary for the formation of a database of modern specialized photopolymer materials and the rationalization of the casting process. The rational parameters (parameters that achieve printing without loss of quality in minimal time) of the additive growing process and data on the thermomechanics and thermal physics of materials are determined for a sample of six modern specialized castable photopolymer resins from different manufacturers.

2.1. Specialized Castable Photopolymer Resins

The list of photopolymer materials considered in the current study includes the developments of the Russian companies Scientific and Production Enterprise 3D Additive Technologies LLC (Nizhny Novgorod, Russia) and Harz Labs LLC (Moscow, Russia), as well as foreign manufacturers Yongchanghe Technology Co., Ltd. (Shenzhen, Guangdong Province, China) and Siraya Tech (Los Angeles, CA, USA). Specialized castable

photopolymer resins, which can be used in the frames of the technology of investment casting, have been considered. Six castable photopolymer resins are considered: Harz Labs Dental Cast Cherry (Harz Labs LLC); Gorky Liquid Castable (Scientific and Production Enterprise “3D Additive Technologies”); Gorky Liquid Dental Castable (Scientific and Production Enterprise “3D Additive Technologies”); JAMG HE Ultra Cast UV Resin (90% WAX) (Yongchanghe Technology Co., Ltd.); JAMG HE Jewelry Casting Resin (25% WAX) (Yongchanghe Technology Co., Ltd.); Siraya Tech Cast Royal Blue (Siraya Tech). Figure 1 shows the liquid (viscous) phase of photopolymer materials before curing.

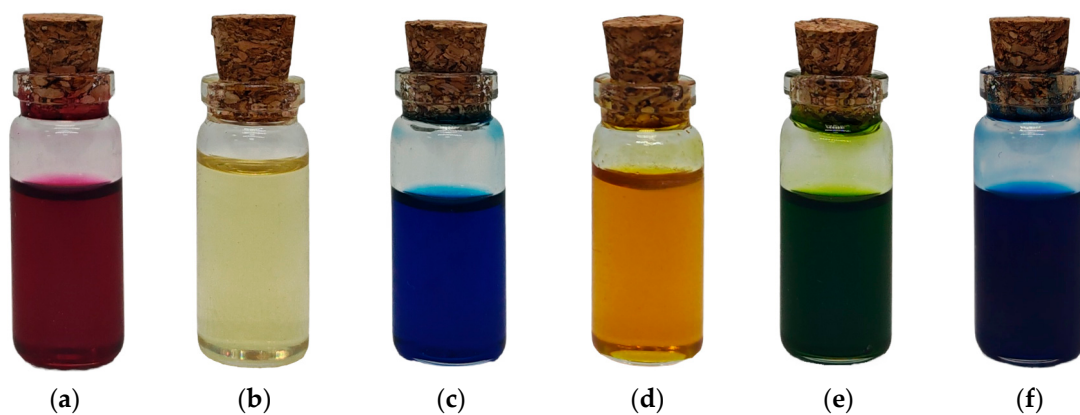


Figure 1. Liquid phase of photopolymer resin. (a) HARZ Labs Dental Cast Cherry; (b) Gorky Liquid Castable; (c) Gorky Liquid Dental Castable; (d) JAMG HE Ultra Cast UV Resin (90% WAX); (e) JAMG HE Jewelry Casting Resin (25% WAX); (f) Siraya Tech Cast Royal Blue.

Harz Labs Dental Cast Cherry is positioned as a specialized castable resin. The resin is used for direct metal casting and, according to the manufacturer, has low ash content ($<0.1\%$) and low thermal shrinkage ($<1\%$). The material has been widely used in dentistry for casting crowns, bridges, and implants. The scope of application can be extended to high-tech foundries in the aircraft industry, automotive industry, and mechanical engineering. The material is a translucent viscous liquid of red color before curing.

Gorky Liquid Castable is a castable photopolymer resin used to create castings and molds. Ash content is less than 1% , according to the manufacturer. The material is used for casting dental implants and jewelry. The resin has high viscosity and density. At the same time, the material provides high detail and accuracy of printing. The material is a translucent viscous liquid of pale yellow color before curing.

Gorky Liquid Dental Castable is a translucent yellow/blue material. The material is a translucent blue liquid before curing, as seen in our procurement batch. The material is distinguished for its high strength, elasticity, flexibility, density, and viscosity. The material is considered stable to external force influences and aggressive environments. The material is initially positioned as castable; the manufacturer notes the ash content (1%). Gorky Liquid Dental Castable behaves like a regular injection wax when burned. The material is intended for printing castable models in dentistry.

JAMG HE Ultra Cast UV Resin (90% WAX) is positioned as a castable resin. According to the manufacturer, it has zero ash content due to the high content of wax (approximately 90%). The photopolymer resin is used for investment casting of metals and alloys. The material is intended for 3D printing of jewelry blanks, dental prostheses, and engineering blanks. Thermal shrinkage of the material is $0.3\text{--}0.6\%$; viscosity is $80\text{--}150\text{ MPa}\cdot\text{s}$. The material is also suitable for injection molding and veneer molding. The material is a translucent viscous liquid of yellow color before curing.

JAMG HE Jewelry Casting Resin (25% WAX) is used for the investment casting of metals and alloys. The wax content is 25% , and it has a low ash content ($<0.1\%$) and low

thermal shrinkage (0.2–0.5%). In its chemical composition, the resin is close to melting wax and has found wide application in casting jewelry and engineering blanks. The resin makes it possible to print thin-walled products and minimize post-treatment due to low thermal shrinkage. The material is a translucent viscous liquid of light green color before curing.

Siraya Tech Cast Royal Blue is designed for 3D printing and investment casting. The wax content is 20%. According to the manufacturer of the material, it combines the properties of Cast Purple and Cast True Blue resins, creating the optimal balance for casting. The resin provides a good surface quality and volume of the material, has easy printing, and has a low ash content. The percentage of ash content is not represented by the manufacturer. The material is a translucent viscous liquid of blue color before curing.

2.2. Additive Growth of Photopolymer Structures

A standard photopolymer DLP printer Anycubic Photon Mono M7 Pro (wavelength 405 nm) was used to determine the rational printing parameters of photopolymer resins. The test model of the printer was used to determine the main printing parameter—the exposure time (the time taken to cure one layer, 0.05 mm thick). The initial printing time was set as the minimum value specified by the manufacturer. Eight test models (Figure 2) with different exposure times were printed simultaneously in one technological cycle for each resin separately. This helped to quickly determine the rational time, or the individual value at which quality printing was performed for each resin. The test model includes print accuracy indicators: holes of different diameters, columns of different thicknesses, sphere, bridge, etc. The quality indicators of the selected test model are comparable with models used in other studies [21]. The parameters of the technological process of the additive layer-by-layer growth of structures were also worked out on models such as a ladder and cubes of different sizes. Ladder-type models were printed with height increments of 1 mm and 5 mm in 10 steps, so as to determine the amount of model shrinkage during printing. The ladder-type model revealed that shrinkage occurs only in the base layers due to over-curing of the material. Therefore, shrinkage will always be the same, regardless of the model size. Cube-type models were printed with sides of 5 mm, 10 mm, and 15 mm. This allowed us to determine that shrinkage occurs only along the Z-axis. Measurements were taken using calipers with an accuracy of 0.01 mm. The selected rational parameters of the technological process of layer-by-layer cultivation are presented in Table 1.

Table 1. The rational parameters of the production process.

Photopolymer Resin	3D Printing Process Parameters		
	Exposure Time, s	Base Layer Time, s	Shrinkage, mm
HARZ Labs Dental Cast Cherry	4.00	100	0.05
Gorky Liquid Castable	6.00	50	0.02
Gorky Liquid Dental Castable	9.00	15	0.05
JAMG HE Ultra Cast UV Resin (90% WAX)	6.25	30	0.05
JAMG HE Jewelry Casting Resin (25% WAX)	25.00	150	0.05
Siraya Tech Cast Royal Blue	10.75	20	0.00

Gorky Liquid Dental Castable photopolymer resin has a lower viscosity, which leads to an increase in material consumption. JAMG HE Jewelry Casting Resin (25% WAX) showed poor adhesion to the platform on which the model is formed. This leads to difficulties in growing models with a small platform interface.

Test samples of materials after curing obtained within the selected rational printing parameters are shown in Figure 2.

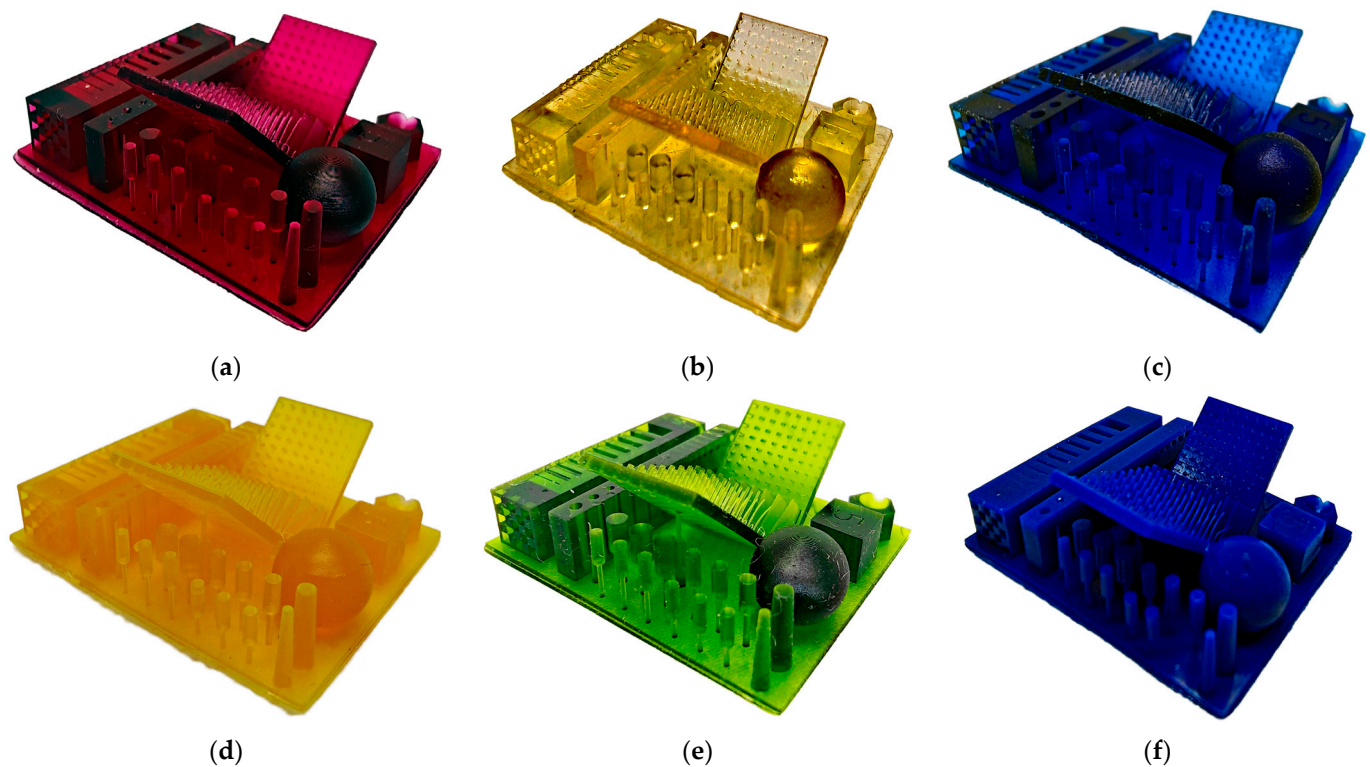


Figure 2. Photopolymer resin after curing: (a) HARZ Labs Dental Cast Cherry; (b) Gorky Liquid Castable; (c) Gorky Liquid Dental Castable; (d) JAMG HE Ultra Cast UV Resin (90% WAX); (e) JAMG HE Jewelry Casting Resin (25% WAX); (f) Siraya Tech Cast Royal Blue.

Plastic structures with varying degrees of transparency and brittleness represent all photopolymer materials after curing.

When testing the current sample of photopolymer materials, there were no problems with the selection of parameters for the additive growth of structures. The rationalization of the technical process parameters made it possible to eliminate or minimize the main defects: sagging of bridge elements, bending and warping of thin-walled elements, parasitic illumination, “elephant foot” effect, etc. Rational printing parameters established as part of the development of the technological process of layer-by-layer growth of photopolymer models have significant differences from the recommendations of manufacturers (if any).

The analysis of the influence of the parameters of the production process of photopolymer printing is noted as an important factor for the development of materials and technologies [22]. Print parameters ensure the high quality of the grown model and minimize post-processing. The final selection of parameters depends on the properties and composition of the resin. However, the printing parameters offered by manufacturers often do not allow us to obtain a high-quality model of the product and the structure of the material [23–25]. This leads to the need for additional surveys in the field of working out the production process of growing products and adjusting the parameters of the production process recommended by the manufacturer. In this current study, the deviation of the parameters of the additive production process from the manufacturer’s recommendations was established by a maximum of several times. It is worth noting that the parameters of the production process also affect the formation time of additive products. This means that the correct selection of process parameters makes it possible to minimize time factors.

2.3. Experimental Research

2.3.1. Thermogravimetric Analysis

An analysis of the change in the mass of the sample over time with a change in temperature was performed as part of the first experiment. TGA for photopolymer resins was performed on the Discovery TGA device (TA Instruments, New Castle, DE, USA) in an oxidized medium (Figure 3). A small mass of material after curing, which is separated from samples of any geometric configuration, is used within the TGA.

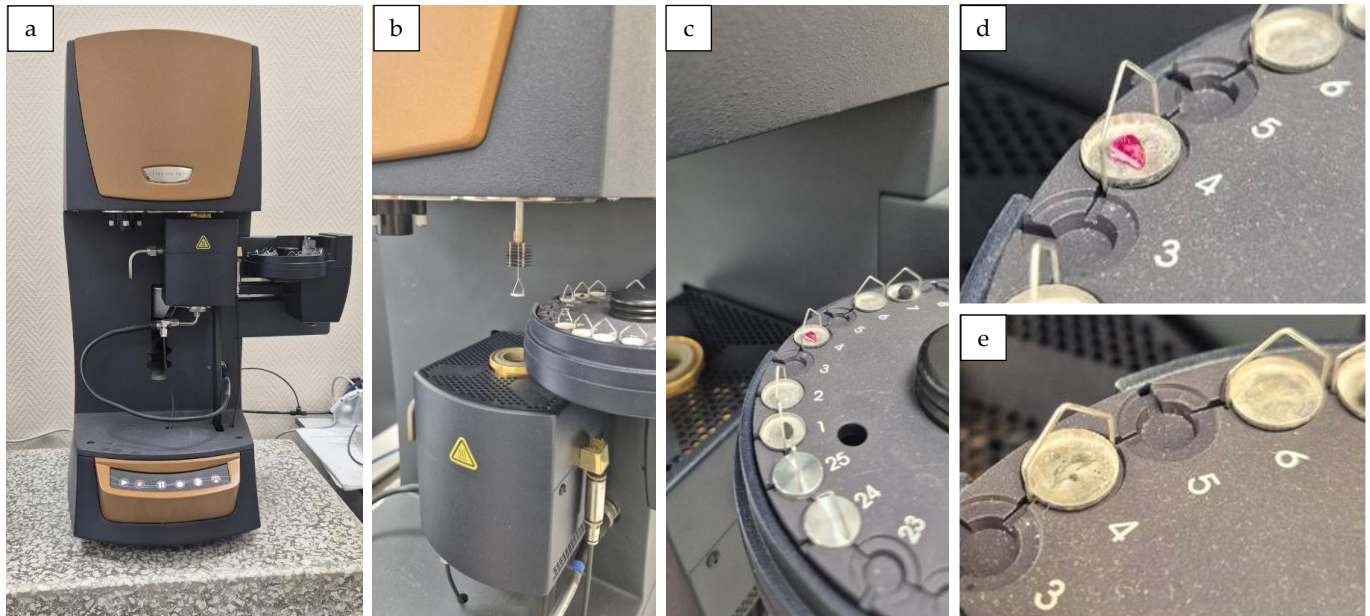


Figure 3. Thermogravimetric analysis of photopolymer resins after curing. (a–c) Experimental plant of Discovery TGA. (d) Sample before thermal destruction. (e) Sample after thermal destruction (the sample is Harz Labs Dental Cast Cherry).

During the experiment, the samples were heated to approximately 700 °C at a constant speed of 10 °C/min. The experiment was carried out in accordance with the international standard ISO 7111:1987 “Plastics. Thermogravimetric analysis of polymers. Temperature scanning method”.

Dependencies of the residual mass of the samples with a change in temperature were obtained as part of the experiments.

2.3.2. Dynamic Mechanical Analysis

The next stage of the study was a series of DMA experiments. Studies were conducted using DMA Q800 (TA Instruments, New Castle, DE, USA), a three-point bending experiment scheme (Figure 4). The investigations were conducted in accordance with ASTM D790-10 for composite polymers using flat bending tests. The oscillating frequency was 1 Hz. The heating rate was 5 °C/min over a temperature range from 0 °C to 225 °C.

Rectangular samples of 60 × 12 × 3 mm were grown within the selected rational process parameters. The samples were subjected to standard post-polymerization for 30 min. Samples were grown with different printing directions within the Cartesian coordinate system for the main material sample. Harz Labs Dental Cast Cherry samples were also grown at 45° using supports. Different printing directions were chosen to evaluate their effect on the viscoelastic properties of the materials.

For the study, at least five samples were grown in each direction. The samples did not have visual defects and pores (visual analysis with translucent materials is possible). Three samples were taken from the lot for the experimental study. DMA makes it possible

to obtain data without leaving the zone of linear viscoelasticity. This makes it possible to describe the material with simple models—for example, a generalized Maxwell body.

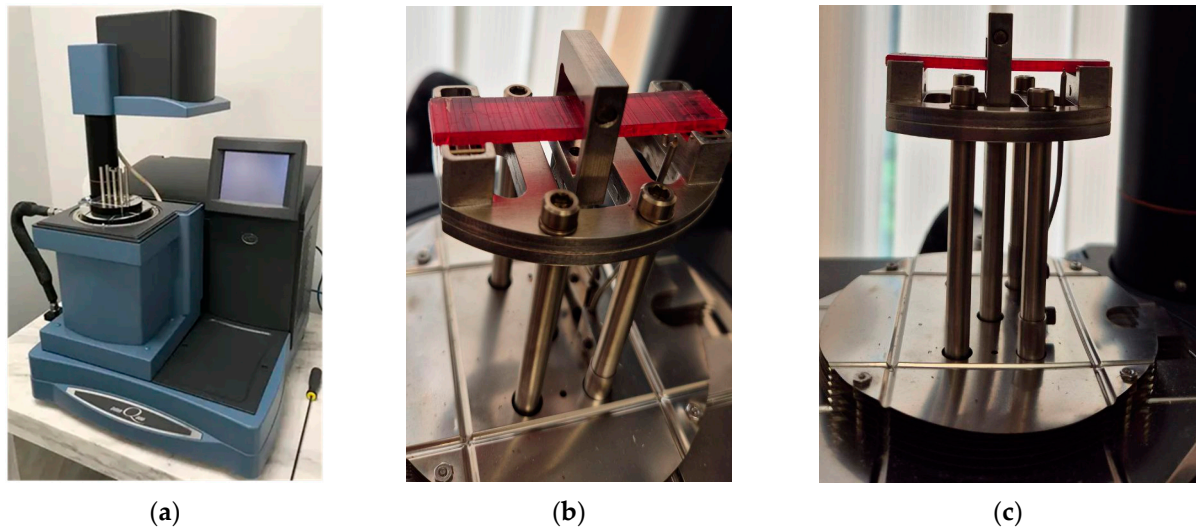


Figure 4. Dynamic mechanical analysis of photopolymer resins after curing: (a) experimental installation of DMA Q800; (b,c) three-point bending (different angles). The sample is Harz Labs Dental Cast Cherry.

3. Results and Discussion

3.1. Thermogravimetric Analysis

Thermogravimetric (TG) curves are obtained within the TGA. The TG curves show the dependence of the residual weight of the material on temperature (Figure 5).

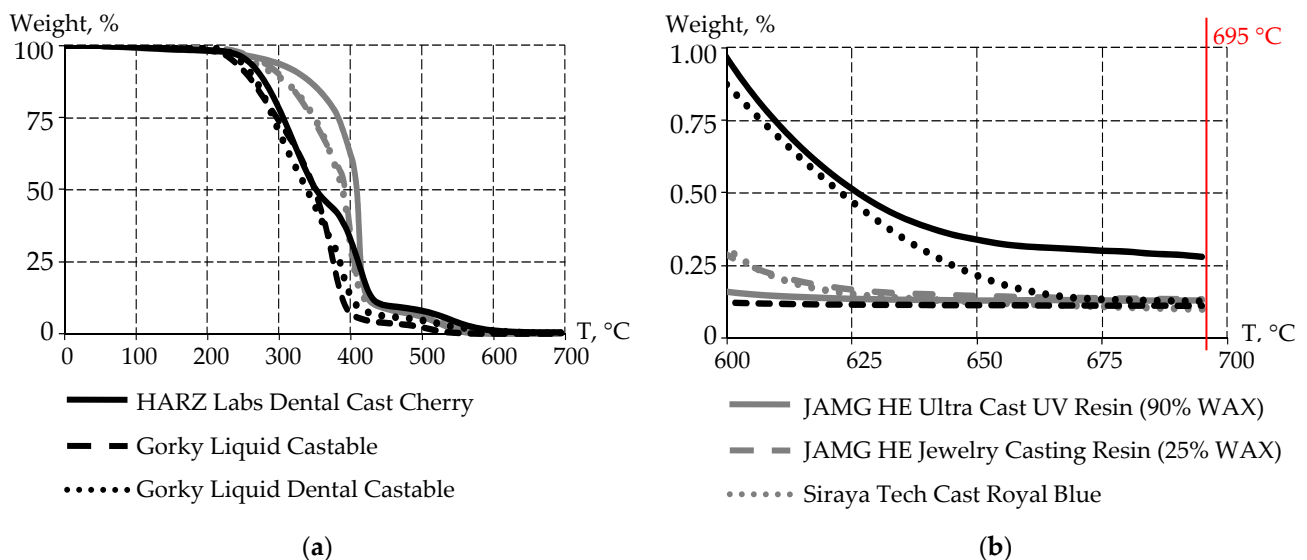


Figure 5. Thermogravimetric analysis. (a) The full temperature range. (b) Temperatures over 600 °C.

Thermal destruction of all considered materials begins at temperatures of 50 °C. At temperatures of up to 225 °C, the mass of the samples varies slightly, and the residual mass of the material is within 95%. Kavun et al. note that mass losses up to 7% correspond to the loss of moisture and volatile components [26]. In the temperature range from 225 to 400–450 °C, a rapid decrease in the mass of the samples is observed. It can be noted that the range of decomposition temperatures of the organic components of the castable photopolymers coincides with ceramic photopolymer composites [26]. However, they

have a much higher rate of destruction. At temperatures above 410 °C, the process of thermal decomposition of materials slows down. A more uniform thermal decomposition of photopolymer resins produced by Yongchanghe Technology Co., Ltd. and Siraya Tech can be noted. Russian photopolymer resins have lower onset temperatures of rapid degradation with higher decay rates but longer ranges of relatively rapid thermal degradation. At a temperature of 600 °C or more, all materials have less than 1% of the residual weight. This confirms their specialization for casting technologies. Thermostable photopolymer materials at temperatures of 600 °C and more have more than 20% of the residual weight [26,27]. The castable photopolymers have destruction start temperatures five or more times less than thermostable materials.

The first derivatives of thermogravimetric curves (DTG) were obtained to analyze the decomposition rate of cured photopolymer resins. DTG curves show mass loss per unit temperature. The TG and DTG curves are shown in comparison for the entire set of materials in Figure 6.

It can be noted that Russian materials are less stable within the framework of temperature destruction. A non-linear abrupt change in the rate of thermal decomposition of the material is observed in Harz Labs Dental Cast Cherry and Gorky Liquid Dental Castable. This may be due to chemical reactions in the material, requiring additional analyses. The remaining materials considered have a pronounced peak in the decomposition rate of the material: 375 °C for Gorky Liquid Castable; 415 °C for JAMG HE Ultra Cast UV Resin (90% WAX); 380 °C for JAMG HE Jewelry Casting Resin (25% WAX); 400 °C for Siraya Tech Cast Royal Blue. The DGT peaks correspond to the thermal decomposition and oxidation of organic substances [26]. The rapid decomposition temperature range has strong differences between materials. The minimum temperature range for rapid thermal destruction is JAMG HE Ultra Cast UV Resin (90% WAX), approximately 100 °C [345; 445]. The maximum temperature range for rapid thermal destruction is the Russian Harz Labs Dental Cast Cherry material, approximately 200 °C ([260; 440] °C).

It can also be noted that non-castable photopolymers and composites based on them have a single-stage decomposition with a pronounced DGT peak [28,29]. In this case, the thermal decomposition of castable photopolymers has several stages of decomposition with different rates of destruction. Harz Labs Dental Cast Cherry has the maximum number of stages of thermal decomposition. If negative effects are detected when burning Harz Labs Dental Cast Cherry from casting molds, chemical analysis of the material during thermal destruction may be required.

The indicators of the temperature destruction of the materials under consideration are presented in Table 2. Start temperature rapid destruction corresponds to the moment when mass loss becomes greater than 1%. The minimum percentage of residual mass of materials at the end of the thermal decomposition cycle is shown in Figure 7.

Table 2. Temperature destruction of photopolymer materials.

Photopolymer Resin	Rapid Destruction		Weight Less than 1%	
	T, °C	Weight, %	T, °C	Weight, %
HARZ Labs Dental Cast Cherry	260	93.97	600	0.964
Gorky Liquid Castable	240	93.92	530	0.831
Gorky Liquid Dental Castable	245	94.74	595	0.968
JAMG HE Ultra Cast UV Resin (90% WAX)	345	87.28	555	0.972
JAMG HE Jewelry Casting Resin (25% WAX)	300	90.24	580	0.768
Siraya Tech Cast Royal Blue	315	86.05	580	0.939

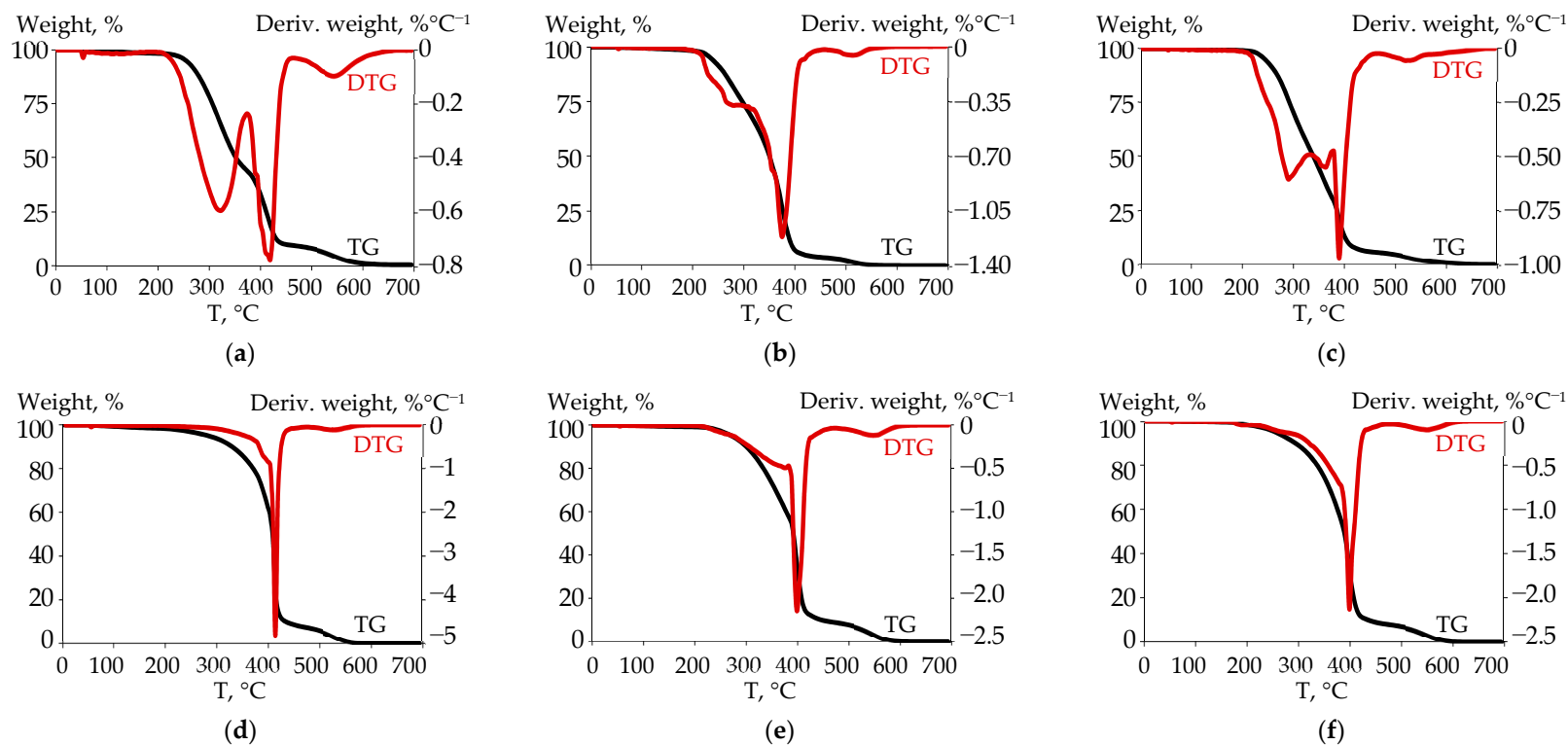


Figure 6. TG and DTG curves of photopolymer resins after curing: (a) HARZ Labs Dental Cast Cherry; (b) Gorky Liquid Castable; (c) Gorky Liquid Dental Castable; (d) JAMG HE Ultra Cast UV Resin (90% WAX); (e) JAMG HE Jewelry Casting Resin (25% WAX); (f) Siraya Tech Cast Royal Blue.

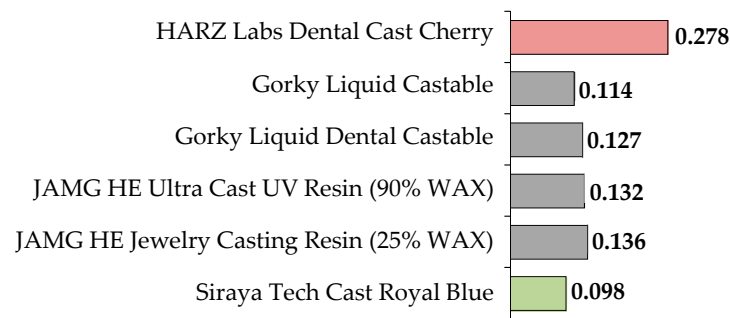


Figure 7. Weight (%) at 695 °C.

Less than 1% of the residual weight of the material is observed at temperatures of 530 °C and more. Gorky Liquid Castable has the fastest thermal decomposition (less than 1% at temperatures from 530 °C) and is one of the materials with a minimum residual weight of 0.114% at 695 °C. The minimum ash content is in Siraya Tech Cast Royal Blue (less than 0.1%).

Harz Labs Dental Cast Cherry has the following characteristics: a minimum temperature at the beginning of rapid thermal destruction, the maximum length of the zone of rapid thermal destruction, the maximum temperature of the residual mass is less than 1%, and the maximum residual ash content is 0.278% at a temperature of 695 °C. The experimentally obtained percentage of ash content is greater than that declared by the manufacturer (approximately 3 times).

Materials of Yongchanghe Technology Co., Ltd. also did not confirm the ash content declared by the manufacturer. JAMG HE Ultra Cast UV Resin (90% WAX) has 0.132% residual weight, which does not correspond to zero ash content. JAMG HE Jewelry Casting Resin (25% WAX) has 0.136% residual weight, which does not correspond to the ash content of less than 0.1%.

Only one material from the sample under consideration has an ash content of less than 0.1%. This is Siraya Tech Cast Royal Blue produced by Siraya Tech (Los Angeles, CA, USA).

In general, all the materials in question have low ash content but have a different nature of changing the rate of thermal decomposition. This must be taken into account when forming a map of the technological process of burning out a photopolymer model when forming a casting mold and selecting materials for its molding.

3.2. Dynamic Mechanical Analysis

The dependencies of the storage modulus, the loss modulus, and the tangent of the angle of mechanical losses for samples additively grown in different printing directions were obtained for all the materials under consideration. The dependence of thermomechanical properties on temperature, according to the example of Harz Labs Dental CAST Cherry (samples printed in the *y*-axis direction), are shown in the same coordinate axes in Figure 8. These are curves averaged over three measurements. Average standard deviation by parameters: 32.64 MPa—storage modulus; 3.54 MPa—loss modulus; 0.004—mechanical loss angle tangent.

The dependence of the thermomechanical properties of the material on temperature makes it possible to establish zones of transition from the vitrified state to the highly elastic one, and with further heating to the viscous one. Harz Labs Dental Cast Cherry begins to lose stiffness at temperatures of 75 °C and reaches a viscous plateau at temperatures of more than 150 °C. As the temperature increases, the storage modulus decreases, which corresponds to the glass transition and structural α -relaxation. The obtained nature of the change in the viscoelastic properties of the photopolymer is consistent with the data obtained by Moharana et al. [30] for the material of the same class.

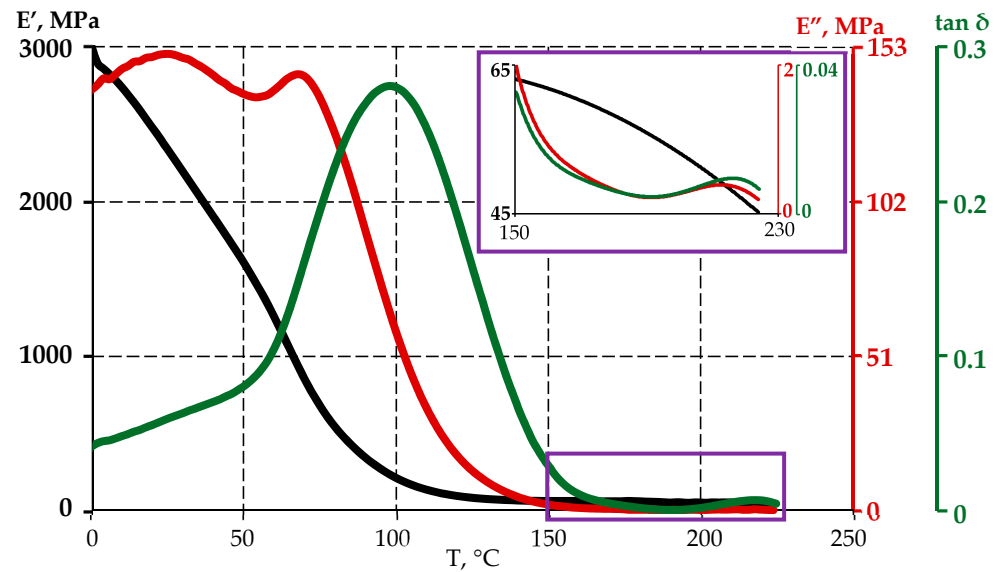


Figure 8. Thermomechanical properties of Harz Labs Dental Cast Cherry: black is the storage modulus E' ; red is the loss modulus E'' ; green is the tangent of the angle of mechanical losses $\tan \delta$; the purple square highlights increases the temperature zone over 150 °C.

The softening temperature of the material is approximately 100 °C according to the $\tan \delta$ signal. These data correlate with the results of Moharana et al. [30] and Musil et al. [31].

The level and nature of temperature dependencies of Harz Labs Dental Cast Cherry show good compliance with the results obtained for other photopolymer materials [32,33]. A wide range of glass transition temperatures is noted in studies of photopolymer materials from other manufacturers [34]. This is also observed in the current study.

3.2.1. The Effect of the Printing Direction on the Thermomechanical Properties of Additively Grown Photopolymer Structures

The analysis of the effect of the printing direction is shown by the example of Harz Labs Dental Cast Cherry (Figure 9). This is due to the fact that for the material, printing is considered not only in the directions of the Cartesian coordinate system but also printing at an angle of 45° using supporting structures.

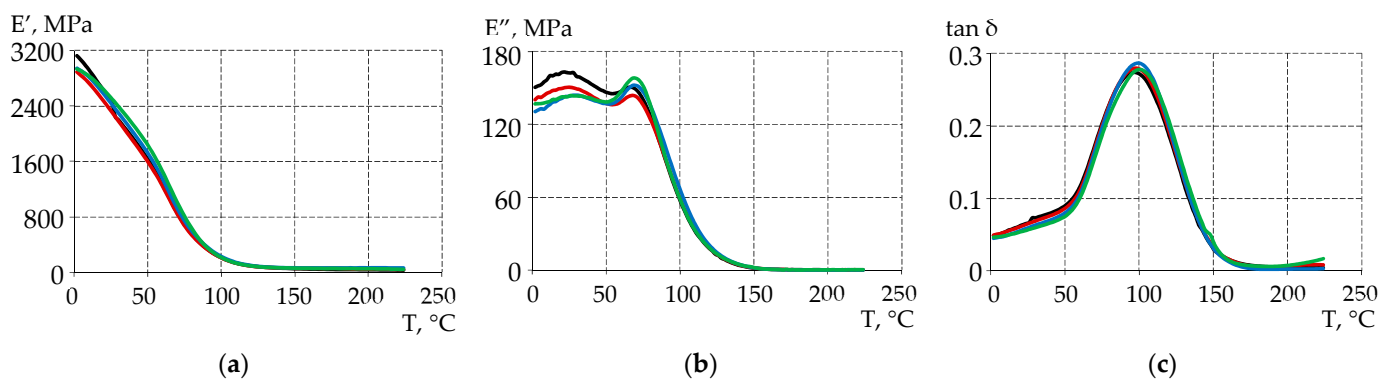


Figure 9. Thermomechanical properties of Harz Labs Dental Cast Cherry: (a) is the storage modulus E' ; (b) is the loss modulus E'' ; (c) is the tangent of the angle of mechanical losses $\tan \delta$; black is x-axis; red is y-axis; blue is z-axis; green is 45°.

The main effect of the image printing direction is observed when the loss modulus and the tangent of the angle of mechanical losses change in the temperature range up to 75 °C. The nature of the distribution of parameters is uniform. At temperatures of more than 150 °C, some samples show insignificant fluctuations in the tangent of the angle of

mechanical losses. This effect may be associated with the presence of additive growth defects that were not observed during visual inspection: lack of conjugation between layers, pores, etc. Figure 9 shows the averaged data for each printing direction. The glass transition/softening temperature according to the loss angle tangent signal is observed near 100 °C. However, according to the signals of the storage modulus and the loss modulus, the relaxation processes in the materials cover a fairly wide range from 50 to 150 °C. The printing direction affects the storage modulus and the loss modulus ($x > y > z$) at temperatures up to 100 °C. The printing direction has a small effect on the glass transition/softening temperature of the material according to the signal of the tangent of the loss angle. This shows a strong dependence of the glass transition on the molecular structure of the material and independence from the orientation of the printing layer. Similar trends were established by Štaffová et al. when analyzing the temperature and mechanical reactions of photopolymer structures grown in different printing directions [35].

The quantitative influence of the printing direction on the viscoelastic characteristics of the material is presented in Table 3 within the relative percentage deviation (reference value of the printing on the coordinate x) and the standard deviation.

Table 3. The analysis of the effect of the printing direction on the thermomechanical characteristics of additively grown structures.

Parameter	Evaluation Measure	$\Delta_{x,y}$, %	$\Delta_{x,z}$, %	$\Delta_{x,45}$, %	σ
E' , MPa	Average	12.127	10.969	10.932	39.237
	Maximum	48.384	32.968	19.558	158.245
E'' , MPa	Average	15.339	15.477	11.192	3.260
	Maximum	67.427	96.601	85.685	10.661
$\tan \delta$	Average	18.402	12.962	13.909	0.005
	Maximum	77.346	98.225	79.897	0.009

The comparison of results was carried out using the Formulas (1)–(3):

$$\Delta_{x,y} = |A_x - A_y| / A_x \times 100 \quad (1)$$

$$\Delta_{x,z} = |A_x - A_z| / A_x \times 100 \quad (2)$$

$$\Delta_{x,45} = |A_x - A_{45}| / A_x \times 100 \quad (3)$$

where A_x is the value of thermomechanical parameters obtained during printing along the x -axis; A_y is the value of thermomechanical parameters obtained during printing along the y -axis; A_z is the value of thermomechanical parameters obtained during printing along the z -axis; A_{45} is the value of thermomechanical parameters obtained when printing at an angle of 45°; A is storage modulus E' , loss modulus E'' and loss tangent $\tan \delta$ (comparison was performed for each parameter separately).

The average deviation of thermomechanical parameters when changing the printing direction is not more than 20%. The maximum deviations of thermomechanical parameters when changing the printing direction can differ by almost 2 times and are observed at the maximum values of the parameters. It is worth noting that Shim et al. [36] determined the level of deviation of about 30% of the flexural strength at three-point bending of samples grown within the printing direction of 0 and 90°. This correlates with the data of the current study.

3.2.2. Comparative Analysis of the Thermomechanics of Photopolymer Materials

The maximum temperature of DMA for materials varied from 205 to 225 °C and depended on the behavior of the material, as well as the conditions for non-exit from the zone of linear viscoelasticity. A comparative analysis of the experimental data on the thermomechanics of a set of photopolymer materials is shown in the temperature range from 0 to 200 °C (Figure 10). The data is shown for the printing direction on the x coordinate.

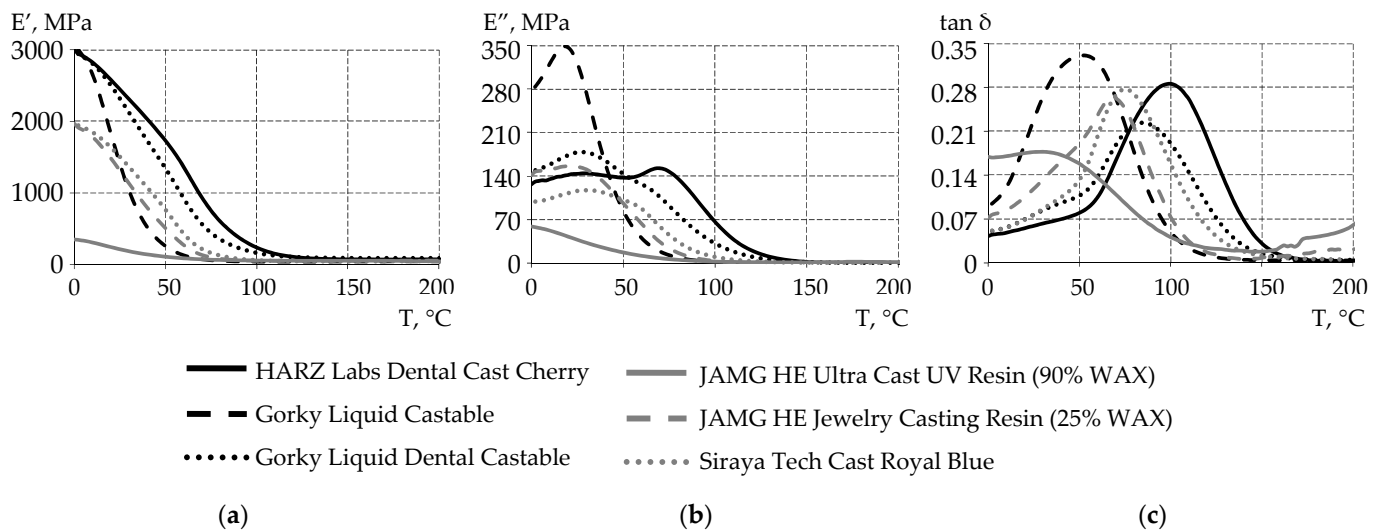


Figure 10. Thermomechanical properties of photopolymer materials: (a) the storage modulus E' ; (b) the loss modulus E'' ; (c) the tangent of the angle of mechanical losses $\tan \delta$.

Russian photopolymer resins Harz Labs Dental Cast Cherry, Gorky Liquid Castable, and Gorky Liquid Dental Castable with printing directions within the Cartesian coordinate system have an initial storage modulus of 3000 MPa. As the temperature increases, the storage modulus decreases at different rates. The temperature of the beginning of the decrease in the stiffness of materials can be estimated from the signal of the loss modulus: 20–30 °C for Gorky Liquid Castable and Gorky Liquid Dental Castable; 75 °C for Harz Labs Dental Cast Cherry. Exit to the rubber plateau is observed at 80 °C for Gorky Liquid Castable and at 150 °C for Harz Labs Dental Cast Cherry and Gorky Liquid Dental Castable. Gorky Liquid Castable has a maximum loss modulus in the temperature range from 0 to 40 °C. This means that the material at temperatures up to 40 °C dissipates mechanical energy more efficiently during deformation and has more pronounced damping properties. The increase in the Liquid Dental Castable loss modulus in the range of 0 to 20 °C is characterized by structural changes in the materials and may be associated with an increase in the crosslinking density. A similar but less pronounced effect is observed in Gorky Liquid Dental Castable up to a temperature of 30 °C. Harz Labs Dental Cast Cherry remains in a vitrified state until approximately 75 °C. This is the maximum indicator of all the materials considered. The glass transition temperature, according to the $\tan \delta$ signal, is 52 °C for Gorky Liquid Castable, 84 °C for Gorky Liquid Dental Castable, and 100 °C for Harz Labs Dental Cast Cherry.

The maximum level of the JAMG HE Jewelry Casting Resin (25% WAX) and Siraya Tech Cast Royal Blue storage modulus is about 1000 MPa less compared to Russian photopolymers. The temperature of the beginning of the decrease in stiffness of JAMG HE Jewelry Casting Resin (25% WAX) and Siraya Tech Cast Royal Blue is comparable to Gorky Liquid Castable and Gorky Liquid Dental Castable: approximately 25 °C. The effect of increasing the crosslinking density of JAMG HE Jewelry Casting Resin (25% WAX) and

Siraya Tech Cast Royal Blue is observed at temperatures up to 25 °C. JAMG HE Jewelry Casting Resin (25% WAX) and Siraya Tech Cast Royal Blue reach a viscous plateau at a temperature of 100 and 125 °C, respectively. The glass transition temperature of JAMG HE Jewelry Casting Resin (25% WAX) and Siraya Tech Cast Royal Blue is observed at approximately 65 and 75 °C, respectively. JAMG HE Jewelry Casting Resin (25% WAX) and Siraya Tech Cast Royal Blue have small differences in terms of thermoviscuity. This may be due to a close wax percentage of 20–25%.

The minimum values of the storage modulus and the loss modulus are observed in JAMG HE Ultra Cast UV Resin (90% WAX). The maximum level of the storage modulus is approximately 300 MPa. The maximum level of the loss modulus is approximately 62 MPa. This is the softest material from the sample of photopolymers under consideration. The signals of the storage modulus and the loss modulus, as well as the tangent plateau of the mechanical loss angle, in the temperature range from 0 to 30 °C JAMG HE Ultra Cast UV Resin (90% WAX) indicate the achievement of a stable crosslinking density of the material and stabilization of dynamic properties. As the temperature increases, the material begins to lose stiffness. This may be due to a high wax content. The glass transition temperature of JAMG HE Ultra Cast UV Resin (90% WAX) is observed at approximately 30 °C. Fluctuations in the tangent of the angle of mechanical losses are observed at temperatures of more than 150 °C. This may be due to the onset of structural degradation due to the high content of wax.

The nature of the change in the modulus of material losses has differences. According to the signals of the loss modulus, relaxation processes in materials occur at different temperature ranges: Harz Labs Dental CAST Cherry and Gorky Liquid Dental Castable at a temperature of 150 °C, Gorky Liquid Castable and JAMG HE Jewelry Casting Resin (25% WAX) at a temperature of 100 °C, and Siraya Tech Cast Royal Blue at a temperature of 125 °C. JAMG HE Ultra Cast UV Resin (90% WAX) does not have a pronounced relaxation transition zone.

The effect of the printing direction on the thermomechanical properties of the entire set of castable photopolymer materials within the range of glass transition temperatures and the average standard deviation of the storage modulus, the loss modulus, and the tangent of the angle of mechanical losses is shown in Table 4.

Table 4. Thermomechanics of photopolymer materials.

Photopolymer Resin	T_g , °C	Influence of Printing Direction *		
		$\Delta\sigma$ (E', MPa)	$\Delta\sigma$ (E'', MPa)	$\Delta\sigma$ (tan δ)
HARZ Labs Dental Cast Cherry	94–100	32.641	3.538	0.004
Gorky Liquid Castable	45–55	23.304	3.563	0.005
Gorky Liquid Dental Castable	84–88	33.849	2.894	0.003
JAMG HE Ultra Cast UV Resin (90% WAX)	30–32	3.826	0.400	0.014
JAMG HE Jewelry Casting Resin (25% WAX)	65–68	7.414	2.931	0.007
Siraya Tech Cast Royal Blue	74–78	29.695	2.818	0.002

* includes only three directions of printing samples within the Cartesian coordinate system.

It can be noted that the printing direction has a minimal effect on the glass transition temperatures of materials. The minimum glass transition temperature is observed in JAMG HE Ultra Cast UV Resin (90% wax), a photopolymer with a maximum wax content. The maximum glass transition temperature is Harz Labs Dental Cast Cherry.

The minimum average standard deviation of the storage modulus and the loss modulus is observed in JAMG HE Ultra Cast UV Resin (90% WAX), while the material has a maximum average standard deviation of the tangent of the angle of mechanical losses. The

maximum average standard deviation is observed in Harz Labs Dental Cast Cherry. The maximum average standard deviation is observed in Gorky Liquid Castable. The minimum average standard deviation of the tangent of the angle of mechanical losses is observed in Siraya Tech Cast Royal Blue.

In general, all materials of the sample showed fairly stable thermomechanical properties. The thermomechanics of materials are important factors for the formation of the technological process of burning a photopolymer model when obtaining high-quality casting molds.

As part of the development of the work, it is required to analyze the influence of the direction of printing of all photopolymers at angles of inclination—taking into account the supporting structures—as well as to determine the dependence of the coefficients of thermal expansion of materials on temperature.

4. Conclusions

Within the framework of this work, six modern specialized castable resins of different manufacturers were selected to assess the possibility of their implementation in the framework of industrial processes of investment casting.

A significant difference between the parameters of the additive growth process of material structures recommended by the manufacturer and those established as part of the development of the technological process is confirmed. The exposure time for Harz Labs Dental Cast Cherry was reduced by a factor of 4, and the curing time for base layers was reduced by a factor of 3.6. The exposure time and curing time for base layers were reduced by a factor of 2 for JAMG HE Ultra Cast UV Resin (90% WAX). The exposure time and curing time for base layers were reduced by a factor of 1.5 for the remaining materials.

TGA and DMA were chosen as the main methods of studying the material. TGA was performed at temperatures up to 700 °C. DMA was performed up to temperatures of the rapid destruction of materials, not more than 225 °C.

As part of the TGA, the following were established:

- Thermal destruction begins at temperatures of 50 °C. In the temperature range from 225 to 400–450 °C, a rapid decrease in the mass of the samples (rapid destruction) is observed. Less than 1% of the residual weight of the material is observed at temperatures of 530 °C and more.
- Harz Labs Dental Cast Cherry has a maximum residual ash content of 0.278% at a temperature of 695 °C. The minimum ash content is Siraya Tech Cast Royal Blue (less than 0.1%).

TGA showed that, according to manufacturers, the ash content of materials can be greatly underestimated.

As part of the dynamic mechanical analysis, the following were established:

- The average deviation of thermomechanical parameters when changing the printing direction is not more than 35% for the entire set of photopolymer materials.
- Russian photopolymer materials have an increase or a plateau of the loss modulus at temperatures up to 75 °C, characterized by structural changes in the materials, and may be associated with an increase in the crosslinking density.
- Harz Labs Dental Cast Cherry has the highest glass transition temperature of 94–100 °C.

The data on the thermal physics and thermomechanics of photopolymer materials after curing will be used in the formation of a numerical analog necessary for predicting the stages of the technological process of investment casting. The formation of data on

the temperature dependencies of the thermal expansion coefficient is also one of the main directions of the study.

Author Contributions: Conceptualization, A.A.K., D.O.P., and V.I.S.; methodology, A.A.K.; software, A.A.K., D.O.P., and V.I.S.; validation, A.A.K., D.O.P., and V.I.S.; writing—original draft preparation, A.A.K., and D.O.P.; writing—review and editing, A.A.K., and V.I.S.; visualization, A.A.K., and V.I.S.; funding acquisition, V.I.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out with the financial support of the Government of Perm Krai, agreement dated 26 February 2025 No. C-26/940.1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Nefelov, I.S.; Baurova, N.I. A Study of the Influence of 3D Printing Modes on the Tightness of Mechanical Engineering Products Manufactured Using Additive Technologies. *Polym. Sci. Ser. D* **2025**, *18*, 628–633. [\[CrossRef\]](#)
2. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [\[CrossRef\]](#)
3. Zhang, F.; Zhu, L.; Li, Z.; Wang, S.; Shi, J.; Tang, W.; Li, N.; Yang, J. The recent development of vat photopolymerization: A review. *Addit. Manuf.* **2021**, *48*, 102423. [\[CrossRef\]](#)
4. Wang, X.; Liu, J.; Zhang, Y.; Kristiansen, P.M.; Islam, A.; Gilchrist, M.; Zhang, N. Advances in precision microfabrication through digital light processing: System development, material and applications. *Virtual Phys. Prototyp.* **2023**, *18*, e2248101. [\[CrossRef\]](#)
5. Chaudhary, R.; Fabbri, P.; Leoni, E.; Mazzanti, F.; Akbari, R.; Antonini, C. Additive manufacturing by digital light processing: A review. *Prog. Addit. Manuf.* **2023**, *8*, 331–351. [\[CrossRef\]](#)
6. Tsolakis, I.A.; Papaioannou, W.; Papadopoulou, E.; Dalampira, M.; Tsolakis, A.I. Comparison in Terms of Accuracy between DLP and LCD Printing Technology for Dental Model Printing. *Dent. J.* **2022**, *10*, 181. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Ligon, S.C.; Liska, R.; Stampfl, J.; Gurr, M.; Mülhaupt, R. Polymers for 3D printing and customized additive manufacturing. *Chem. Rev.* **2017**, *117*, 10212–10290. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Colorado, H.A.; Gutierrez-Velasquez, E.I.; Gil, L.D.; de Camargo, I.L. Exploring the advantages and applications of nanocomposites produced via vat photopolymerization in additive manufacturing: A review. *Adv. Compos. Hybrid. Mater.* **2024**, *7*, 1. [\[CrossRef\]](#)
9. Wawryniuk, Z.; Brancewicz-Steinmetz, E.; Sawicki, J. Revolutionizing transportation: An overview of 3D printing in aviation, automotive, and space industries. *Int. J. Adv. Manuf. Technol.* **2024**, *134*, 3083–3105. [\[CrossRef\]](#)
10. Liu, Y.Y.; Echeverry-Rendón, M. 3D-printed biodegradable polymer scaffolds for tissue engineering: An overview, current stage and future perspectives. *Next Mater.* **2025**, *8*, 100647. [\[CrossRef\]](#)
11. Gong, H.; Beauchamp, M.; Perry, S.; Woolley, A.T.; Nordin, G.P. Optical approach to resin formulation for 3D printed microfluidics. *RSC Adv.* **2015**, *5*, 106621–106632. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Meshram, R.N.; Lamprou, D.A. Mould-Free Microneedles in a Single Step: 3D Printing with Photopolymer Resins for Transdermal Delivery. *Pharmaceutics* **2025**, *17*, 1498. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Erdoğan, B.S.; Özgün, M.I.; Madenci, E.; Sayinbatur, M.A.; Erci, F. Production of Green Synthesized Zinc Oxide Nanoparticle-Reinforced PMMA-Based Photopolymer Resins on DLP-Based 3D Printers and Characterization. *Polymers* **2026**, *18*, 1229. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Sameni, F.; Ozkan, B.; Karmel, S.; Engdrom, D.S.; Sabet, E. Large Scale Vat-Photopolymerization of Investment Casting Master Patterns: The Total Solution. *Polymers* **2022**, *14*, 4593. [\[CrossRef\]](#) [\[PubMed\]](#)
15. de Camargo, I.L.; Morais, M.M.; Fortulan, C.A.; Branciforti, M.C. A review on the rheological behavior and formulations of ceramic suspensions for vat photopolymerization. *Ceram. Int.* **2021**, *47*, 11906–11921. [\[CrossRef\]](#)
16. Zakeri, S.; Vippola, M.; Levänen, E. A comprehensive review of the photopolymerization of ceramic resins used in stereolithography. *Addit. Manuf.* **2020**, *35*, 101177. [\[CrossRef\]](#)

17. Pszczółkowski, B.; Zaborowska, M. Effect of Layer Exposure Time in SLA-LCD Printing on Surface Topography, Hardness and Chemical Structure of UV-Cured Photopolymer. *Lubricants* **2025**, *13*, 406. [\[CrossRef\]](#)
18. Rudnik, M.; Bronis, M.; Şükrü, A.M.; Anaç, N. Analysis of Mechanical Properties of Cellular Structures Under Static Tensile Loading in Standardized Specimens Manufactured by Photopolymerization. *Materials* **2026**, *19*, 2945. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Konnunaho, P.; Zakeri, S.; Frankberg, E.J.; Levänen, E. Investigation of resin composition and printing parameters on the dimensional accuracy of alumina components fabricated via ceramic vat photopolymerization. *Open Ceram.* **2025**, *22*, 100751. [\[CrossRef\]](#)
20. Ozkan, B.; Khouyi, A.; Tarak, F.; Sameni, F.; Okoruwa, L.; Sabet, E. Black pigment tuning in DLP ceramic printing: A unified strategy for cure control, strength, surface quality, and dimensional precision. *J. Manuf. Process.* **2026**, *166*, 152–169. [\[CrossRef\]](#)
21. Kalilayeva, A.; Zhumashev, D.; Wei, D.; Perveen, A.; Talamona, D. Investigation of Stereolithography Additively Manufactured Components for Deviations in Dimensional and Geometrical Features. *Polymers* **2024**, *16*, 3311. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Turek, P.; Bazan, A.; Kubik, P.; Chlost, M. Development of a Calibration Procedure of the Additive Masked Stereolithography Method for Improving the Accuracy of Model Manufacturing. *Appl. Sci.* **2025**, *15*, 7412. [\[CrossRef\]](#)
23. Radrigez, L.; Naya, G.; Bienvenido, R. Study for the selection of 3D printing parameters for the design of TPU products. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1193*, 012035. [\[CrossRef\]](#)
24. Towaiq, A.; Obaidat, S.; Munami, A.; Ziout, A. An application of the preference selection index decision making method for parameters selection of FDM printing process. *J. Eng. Res.* **2025**, *13*, 636–642. [\[CrossRef\]](#)
25. Cai, R.; Luo, X.; Xie, G.; Wang, K.; Peng, Y.; Rao, Y. Effects of the printing parameters on geometric accuracy and mechanical properties of digital light processing printed polymer. *J. Mater. Sci.* **2024**, *59*, 14807–14819. [\[CrossRef\]](#)
26. Kavun, Y.; Çelikçi, N.; Kerli, S. Radiation shielding, mechanical and structural properties of TiO₂-Doped photopolymer composites fabricated via DLP 3D printing. *Appl. Radiat. Isot.* **2026**, *229*, 112368. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Liu, Y.; Shen, T.; Zhu, N.; Li, K.; Zheng, Z.; Li, S.; Zheng, J. Boosting holographic properties and conversion of epoxy resin and triacrylate photopolymer by inhibition effect of CeO₂ nanorods in polymerization process. *Polym. Test.* **2024**, *132*, 108349. [\[CrossRef\]](#)
28. Robakowska, M.; Gibson, I.; Akkerman, R.; Wurm, F.R.; Gojzewski, H. Towards more homogeneous character in 3D printed photopolymers by the addition of nanofillers. *Polym. Test.* **2023**, *129*, 108243. [\[CrossRef\]](#)
29. Eken, S.; Kavun, Y.; Çelikçi, N.; Kerli, S. Production of bio-based Photopolymer–Colemanite resin composites using 3D DLP printing for advanced radiation protection. *Appl. Radiat. Isot.* **2026**, *229*, 112380. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Moharana, A.P.; Singh, S.S.; Dixit, A.R. Dynamic mechanical and viscoelastic properties of glass fiber reinforced photopolymer composite fabricated using vat-photopolymerization additive technique: Influence of filler volume fraction. *J. Manuf. Process.* **2024**, *130*, 72–86. [\[CrossRef\]](#)
31. Musil, V.; Laa, D.; Ahmadi, M.; Stampfl, J.; Liska, R.; Merna, J.; Ehrmann, K. Thermoplastic-like mechanical performance of heterogeneous photopolymers for additive manufacturing with tailored hyperbranched rubbers. *RSC Appl. Polym.* **2025**, *3*, 1165–1176. [\[CrossRef\]](#)
32. Zhao, L.; Wang, P.; Zhao, X.; Yang, X.; Zhang, Y.; Cheng, B.; Huang, W.; Yu, R. DLP 3D printing of high-performance thermosetting polymers with photothermal dual-curing resin containing reversible covalent bonds. *Chem. Eng. J.* **2026**, *527*, 171873. [\[CrossRef\]](#)
33. Liu, H.-C.; Zhou, X.-X.; Zhou, S.-S.; Zou, Y.; Wang, Y.-L.; Li, X.-Q. Preparation and Properties Study of Itaconic Acid-based Degradable Epoxy Resin Based on Dynamic Covalent Bonds. *Chin. J. Polym. Sci.* **2025**, *43*, 2009–2021. [\[CrossRef\]](#)
34. Sekmen, K.; Rehbein, T.; Jöhlitz, M.; Lion, A.; Constantinescu, A. Curing-dependent thermo-viscoelastic and shrinkage behaviour of photopolymers. *Mech. Mater.* **2023**, *179*, 104566. [\[CrossRef\]](#)
35. Štaffová, M.; Ondreáš, F.; Svatík, J.; Zbončák, M.; Jančář, J.; Lepcio, P. 3D printing and post-curing optimization of photopolymerized structures: Basic concepts and effective tools for improved thermomechanical properties. *Polym. Test.* **2022**, *108*, 107499. [\[CrossRef\]](#)
36. Shim, J.S.; Kim, J.-E.; Jeong, S.H.; Choi, Y.J.; Ryu, J.J. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. *J. Prosthet. Dent.* **2020**, *124*, 468–475. [\[CrossRef\]](#) [\[PubMed\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.