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Research Article

Lifecycle Evaluation of Live Hinges in Automotive Polymer Fasteners Manufactured via Digital Light Processing (DLP): A Study Through Folding Test Analysis

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Abstract – This study investigates the mechanical durability and long-term performance of live hinge regions in automotive polymer fasteners fabricated using the Digital Light Processing (DLP) additive manufacturing method. Live hinges, which serve as essential flexible joints in various automotive applications, are subjected to continuous mechanical stress during operation, necessitating exceptional fold endurance and fatigue resistance to ensure consistent functionality and longevity throughout the vehicle's lifespan. The research systematically evaluates the material characteristics and structural performance of these hinges by conducting repetitive folding tests, designed to replicate real-world conditions, including thermal and mechanical stresses encountered in automotive environments.

In this context, the study explores the influence of various polymer compositions, additive formulations, and DLP processing parameters—such as layer thickness, curing time, and post-processing treatments—on the microstructural integrity and fold endurance of the live hinges. A comprehensive analysis is undertaken to assess the correlation between these variables and the mechanical resilience of the hinges under cyclic loading.

The findings of this research aim to contribute to the advancement of design methodologies and manufacturing techniques for high-performance polymer fasteners in the automotive sector. By optimizing the material and process parameters, the study seeks to enhance the fatigue life, wear resistance, and overall durability of live hinges, thereby facilitating the development of more robust, efficient, and long-lasting automotive components. This work not only provides valuable insights into the material science and mechanical behavior of DLP-manufactured components but also offers practical guidelines for improving design reliability in next-generation automotive fastener systems.

Keywords – Digital Light Processing (DLP), Live Hinges, Automotive Polymer Fasteners, Fold Test Durability, 3D print

1. INTRODUCTION

Additive manufacturing, also known as 3D printing, is a computer-controlled production technique that constructs products layer by layer. This rapidly advancing technology enables the manufacturing, repair, or replacement of parts in various locations, offering significant flexibility. Additionally, 3D printing is considered a potential solution for addressing sustainability challenges in manufacturing. There are several methods of additive manufacturing, each differing in the materials used and the process of layer formation, with each method offering its own set of advantages and limitations. Among these techniques, digital light stereolithography (SLA) is widely recognized for its ability to produce high-resolution objects with superior surface quality, making it ideal for rapid prototyping and manufacturing. Additive manufacturing is extensively used across various industries, including automotive, to expedite sample creation and product development. For instance, the entire body of the Urbee car was manufactured using 3D printing, demonstrating the feasibility of functional end products in the automotive sector. Due to its capacity to produce complex designs, reduce costs, and foster technological and material advancements, the global additive manufacturing market is projected to reach $70.08 billion by 2030 [1].

In SLA technology, photosensitive resins are solidified through photopolymerization by scanning a 3D model layer by layer with a UV laser beam. Resins are not only employed for prototype development but are increasingly used for mass production as well [2]. In the automotive industry, trim fasteners play a crucial role in securing interior and exterior trim components. "Trim" refers to components that enhance the visual and tactile appeal of a vehicle’s interior and exterior. Trim fasteners typically consist of plastic clips, screws, rivets, and similar hardware, and are used in a variety of applications, including door panels, dashboards, bumpers, fenders, and other external trim. These fasteners ensure the secure attachment of components during assembly while allowing for easy disassembly when necessary, thereby streamlining maintenance and repair processes. The use of such fasteners is essential in optimizing assembly workflows and minimizing production costs within the automotive sector.

In this study, the chosen trim fastener is a double-headed anchor that secures the side door trim to the vehicle's metal body. The forces required for insertion and removal are specified by the standards of major automotive manufacturers and must meet ergonomic criteria. To prevent assembly operators from suffering occupational injuries, the maximum insertion force for fasteners inserted with one finger is set at 45 N. This research examines the suitability of bio-based resins for flexible locking mechanisms in automotive fasteners by comparing the performance of fasteners produced from different resin types using the same additive manufacturing technique. Specifically, three different photopolymeric resins, two industrial and one bio-based derived from soybean oil, were produced via the DLP method as clip fasteners. Installation tests were conducted on these fasteners to evaluate their ability to meet the automotive industry’s performance requirements.

2. ADDITIVE MANUFACTURING

Additive Manufacturing, also known as rapid prototyping, refers to the process of creating three-dimensional digital objects by building up materials layer by layer [3]. In the 1980s, Charles W. Hull pioneered 3D printing through the development of stereolithography, leading to the commercialization of 3D printers. The additive manufacturing process involves several key steps. Initially, the object to be produced is designed using CAD/CAM software, which stands for computer-aided design and manufacturing. Once modeled, the parts are exported to the printer using standard tessellation language (STL). The printer interprets the STL file and converts it into 2D slices that are built layer by layer. Unlike traditional manufacturing, additive manufacturing offers faster production times, the capability to produce intricate designs, greater flexibility in material usage, and reduced material waste [4]. A wide range of polymers can be utilized in this technique [5]. Additionally, as a powerful tool for prototyping, additive manufacturing allows designers to identify and rectify potential errors early in the development process. Due to these significant benefits, additive manufacturing is regarded as a transformative force in the global industrial and manufacturing landscape [6].

2.1. Vat Photo Polymerization-VP

The method in which light is used to initiate free radical polymerization is called photopolymerization. It is based on the principle of exposing photoinitiators to ultraviolet light. Photopolymerization ensures fast curing, less energy consumption and less waste generation. With the absorption of UV rays of the appropriate wavelength by the photoinitiator, reagents are formed, which enables the polymerization of monofunctional monomers and the curing of bifunctional monomers by cross-linking. The vat polymerization method is based on the polymerization of liquid photopolymers with UV light. With this 3D printing technology, light-cured resin is selectively hardened in layers [7]. The printing platform is lowered into a single layer thickness in the photoresin bath, called a vat, after each solid 2D thin layer is hardened. This method is repeated by adding another layer on top of the cured layer and continues until a 3D structure is formed. After the 3D structure is formed, the remaining resin is removed from the vessel and the resulting object is removed from the printer. Additive manufacturing technologies using the vat polymerization method are divided into three groups. These; digital light processing method (DLP), continuous liquid interface fabrication method (CLIP) and stereolithography (SLA) method.

2.1.1. Digital light stereolithography method (Stereolithography-SLA)

Stereolithography (SLA) method is to obtain 3D printing by using resins containing photoinitiators, where free radicals can react with light. Free radicals react with monomers and oligomers and form polymer bonds. The UV ray is directed to the photopolymer resin surface by a moving mirror. After the scanned parts harden, the platform descends by one layer thickness and a new layer is scanned. There is a transparent film at the bottom of the boat to allow light to pass through. An aluminum build plate is used to hold the 3D object, sitting on an axis that allows it to be lowered into the vessel and raised after each layer has cured. The object is printed upside down. Layer thicknesses generally vary between 0.01 and 0.05 mm. Thin layers are hardened with photocurable resin and three-dimensional objects are produced. The first photocurable material produced by Hull was a urethane dimethacrylate (UDMA) with a small fraction of acrylic acid. Benzophenone and methyl ethyl hydroquinone/triallyl phosphate were used as photoinitiator. In SLA technology, the curing time varies depending on the resin, but generally varies between 3 and 15 seconds [8]. After obtaining 3D products with SLA, it is necessary to wash the object. To remove the uncured resin remaining on the surface of the material, washing is usually done in isopropic alcohol. Washing should take less than 10 minutes. It should be dried at room temperature for a minimum of 30 minutes to remove the solvent [9]. Additional curing may be done to ensure that the product obtains greater mechanical strength.

2.1.2. Digital Light Processing (DLP)

Digital light processing (DLP) technology is based on localized photopolymerization of liquid resins. With photopolymerization, a 3D product is obtained layer by layer. Although it is very similar to stereolithography (SLA) technology, digital light is used as the energy source. The main difference between them is the light source [10].

3. PHOTO RESINS

With developing technology, a wide variety of resins have been developed to obtain 3D products. The resins used generally consist of monomers consisting of methacrylates or acrylic esters, solvents, photoinitiators and additives [11]. Monomers and oligomers undergo polymerization reactions by increasing the degree of cross-linking with their reactive groups. Most monomers and oligomers used for the SLA method are polyacrylates. Carbons in the vinyl groups of polyacrylates are cross-linked with various monomers thanks to photoinitiators [12]. The molecular weights of the resins also affect the viscosity and indirectly the printing time. Diluents can be added to the resin to adjust the viscosity. Photoinitiators, which can absorb UV or light of different wavelengths, convert the energy of the incoming light into chemical energy [13]. The transfer of reactive radicals to the active groups on monomers and oligomer chains and the formation of longer chains by reacting with other active groups are possible thanks to photoinitiators. As the chains lengthen, the formation of cross-links and curing begins. Methacrylate and acrylate-based monomers are important raw materials for resins because they provide fast reaction, long-term stability and high mechanical properties. However, they limit their applications due to their volumetric shrinkage. Physical and mechanical properties can be modified by adding additives.

3.1. Literature Review and Purpose of the Study

In his study, Martín-Montal [14] utilized a resin composed of a blend of methacrylated monomers and oligomers combined with a photoinitiator, which was printed using stereolithography (SLA). The research found that a shortened curing time impacted the elastic regions of the printed objects but did not significantly affect the harder portions. Zhang [15], in a separate investigation, developed a light-sensitive acrylic resin for SLA 3D printing and explored the influence of different ingredients on the mechanical properties of the cured objects. The study revealed that the inclusion of reactive diluent considerably reduced the tensile strength of the cured parts. As the concentration of the diluent hexanediol diacrylate (HDDA) increased, the toughness of the printed objects decreased. Moreover, adding more of the cross-linking agent pentaerythritol triacrylate (PETA) resulted in an increase in cross-linking density, thus improving the mechanical properties of the printed parts.

Marin [16] focused on the effects of curing parameters on the mechanical properties of a methacrylate-based commercial resin used in SLA, while Romero-Ocana and Molina [17] explored the viability of incorporating cork powder into a novel photo-curable resin for SLA. Their findings indicated that larger cork particles enhanced the resin's thermal and mechanical properties. Similarly, Noe [18] investigated UV-curable coatings made from methacrylated starch, observing that the cured coatings exhibited high hardness, excellent adhesion, and strong solvent resistance. Vincent [19] demonstrated the practical feasibility of synthesizing bio-resins from epoxidized soybean oil, successfully fabricating prototypes with complex designs, including tensile bars and intricate models, using a commercial SLA printer.

Most 3D printing materials are traditionally derived from fossil resources. However, as the life cycle of products increasingly supports the circular economy, the use of renewable materials in additive manufacturing is becoming more critical to promoting sustainability. The depletion of fossil fuels and environmental concerns make the transition to sustainable materials in additive manufacturing imperative. Vegetable oils, such as those from soybeans, corn, potatoes, and even algae, present promising raw materials for the development of biobased photocurable resins. Their biodegradability, low toxicity, and functional versatility make them ideal candidates for the preparation of polymers. While vegetable oils like soybean oil are not inherently polymers, they serve as precursors to monomer chains that can be converted into a range of polymers, thus offering a renewable alternative to petroleum-based materials. Soybean oil-based monomers exhibit structural similarities to those derived from petroleum, making them viable substitutes for conventional biopolymers.

In this study, three distinct photopolymeric resins were produced using the Digital Light Processing (DLP) method for application in automotive clip fasteners. Two of these resins were industrial, while the third was a biobased resin synthesized from soybean oil. Installation tests were performed on the fasteners made from these materials to assess their suitability for meeting the specific requirements of the automotive industry. The evaluation aimed to determine the viability of biobased photopolymeric resins in creating flexible locking mechanisms and enhancing the sustainability of automotive fastener production.

4. MATERIALS AND METHOD

4.1 Materials

In this study, photopolymeric resin obtained from soybean oil was purchased from the Elegoo with the trade name “Plant-based Tough Photopolymer Resin”. The resin with the trade name "Aqua Gray-8K", which has 43 MPa breaking strength, 17300 MPa Young's modulus, 8% breaking elongation and 1.10 g/cm3 liquid density, was purchased from the Phrozen. The resin with the trade name “Onyx Impact Plus”, which has 37 MPa breaking strength, 1175 MPa Young's modulus, 98% breaking elongation and 1.15 g/cm3 liquid density, was also obtained from the Phrozen.

4.2. Hinges production with DLP Printer

The design of the clip on the live hinge to be produced was made using the Catia program. The product design was sliced and turned into 2D layers by transferring the STL extension file to the Chitu Box application. The necessary process parameters for each resin were entered into the Chitu Box application. The file with the “. STL” extension, in which the process parameters were entered, was transferred to the DLP technology 3D printing machine and prints were taken. Printing parameters for the resins used are given in Table 1.

Table 1. Clips Printing Parameters

	Impact Plus	**8K**	**Plant-based**
Layer Thickness (mm)	0.050	0.050	0.050
Number of Layers	5	6	5
Printing Time (s)	14	1.80	14
Base Illumination Time (s)	30	25	30

The printed clips were cleaned of burrs and turned into the final product.

4.3. Curing Process:

Curing is a critical step in enhancing the mechanical properties of polymer parts produced via the Digital Light Processing (DLP) method. After the printing process, the parts are exposed to ultraviolet (UV) light to ensure full polymerization of the photopolymer resins. This post-processing step is essential for improving the strength, durability, and dimensional stability of the printed components. Adequate curing ensures that the material reaches its optimal performance characteristics, which are crucial for applications such as automotive fasteners where mechanical integrity is a priority. We applied 35 C 50 min UV curing of each sample.

4.4. Washing:

Alcohol washing is employed as a post-processing step to remove uncured resin from the surface of the printed parts. After printing, the parts are typically immersed in an isopropyl alcohol (IPA) bath to dissolve and wash away any residual liquid resin that remains on the surface. This process is important to ensure a clean and smooth finish and to prevent defects in the final cured product. Proper washing also enhances the overall appearance and functionality of the parts, reducing the likelihood of surface contamination or material inconsistencies.

4.5. BendingTest

The insertion test was applied to 8 sample live hinge obtained from three different raw materials. The test was carried out at a speed of 100mm/min. A printed plate was used for making standard angle and force for each test cyvle. The visual of the test performed is given in Figure 1.

Figure 1. Bending Test

5.RESULTS

Bending test was applied to a total of 24 clip samples obtained from 3 different raw materials. The data on the bending cycle obtained because of the bending cycle are shown in Table 2. The clips samples shown in the table are coded with the same name as the resin from which they are obtained.

Table 2. Results of Insertion Test

Specimen No	**Impact Plus (rep)**	**8K (rep)**	**Plant-based (rep)**
1	36	3	21
2	37	5	19
3	33	4	19
4	39	4	18
5	32	3	25
6	31	6	24
7	39	6	17
8	33	4	21

According to the data obtained from the test, Impact Plus clips gave the best value and were installed with an average breakage of 35 cycle. The 8K clips were attached with an average breakage of 5 cycle. Plant-based coded clips obtained from soybean oil were attached with the highest value, an average bending cycle without breakage 22 cycle.

6. CONCLUSION

As a result of this study, live hinges intended for use in the automotive industry were successfully fabricated using the Digital Light Processing (DLP) method, employing three distinct photocurable resins. Upon evaluating the industrial resins, it was observed that clips produced from raw materials with higher elongation at break percentages exhibited reduced insertion forces. Due to the unavailability of technical data for the plant-based resin, a comparative analysis based on elongation at break values could not be conducted. Nevertheless, it was concluded that the plant-based resin shows potential suitability for the clip-type fasteners designed for automotive applications.

Conversely, tough resins or high-detail resins, such as 8K model resins, were found to be unsuitable for live hinge geometries due to their lack of flexibility and fold endurance. Given the lower carbon emissions and recyclability of plant-based photopolymeric resins, it is recommended that their mechanical properties be enhanced through the incorporation of various reinforcing agents to improve their applicability in automotive fasteners. This approach could provide a more sustainable and efficient alternative for the production of live hinges within the automotive sector.

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