

Experimental investigation of stereolithography and digital light processing additive manufactured pallets

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Pallets are a tertiary form of packaging used for stacking, storing, protecting, or transporting goods in supply chains. They are utilized as a base for the unitization of goods for logistics and warehousing. Moreover, pallets can be manufactured using wood, plastic, metal, and corrugated paper, which can be used as material-handling equipment. With several products being transported worldwide and with year-on-year growth, it would be beneficial to make lightweight pallets. Such pallets are recyclable, easy to clean, cheap, and durable to maintain and store. Though most of the pallets are widely available for basic purposes, applications involving high-end bio-packings and transportation of special chemicals require specialized pallets to be manufactured like polymers to ensure a negligible chemical reaction, light in weight, and attenuation in freight capacity, thereby widespread reduction in wastage. With advancements, job to job and immediate requirements, additive manufacturing has the potential to close the gap for jobs with short lead times. If the design process of new pallets has limits the creation of specific codes, the transitions will be smoother in rapid prototyping. This work describes the development of polymer pallets by taking advantage of stereolithography (SLA) and digital light processing (DLP) technology for 3D printing pallets in correlation to injection moulding. After the pallets are designed and manufactured, AM technologies can be applied to specified standards, and the pallets then undergo tensile strength, elongation, and hardness tests. The analysis was carried out for configurable geometries adapting to fork lifting, conveyor, racking, and stacking conditions. Analytical and numerical solutions were carried out to understand the stress and deflections for each geometry and its wide range of applications for pallets.

Keywords: *additive, digital light processing, mechanical, morphology, pallet, properties, stereolithography, surface*

1. Introduction

Storage and movement of materials have become very important aspects in the enhancement of trade and the rise of the world economy. The efficient movement of goods has become the need of the hour among industries. With the gradual increase in trade and the need to boost economies, a large number of countries are adopting regulations and policies regarding natural conservation and sustainable development. When these policies are applied to pallets, this shift in regulations creates concerns regarding the utilization, recycling, and reuse of pallets in various domains like transportation, warehousing, and distribution centres [1–5],

where pallets are often employed in a variety of industries.

Most pallets come in wood, paper, plastics, wood-based composites, metals, and so forth. [1, 6–8]. As of 2020, the number of pallet requirements from the food giant FCI (Food Corporation of India) only of the Lucknow region in India was approximately 70,000 tons, involving a colossal cost factor [9]. The number is bound to increase along with the increase in trade between countries in the foreseeable future, with an increase in consumption, trade, and transport. Wooden pallet manufacturing creates a serious environmental issue which requires immediate attention and colossal regulations. For applications involving heavy loads and sensitive package carriers, their use may damage goods. Wood composites provide a suitable

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alternative, but another problem arises during manufacturing as a result of excessive burning, which might damage the material and cause toxic fumes during processing, which is environmentally hazardous for the manufacturer. High moisture absorption is also a factor, and the payload capacity of wooden pallets decreases, causing the safety requirements for transportation to fall below the requisite parameters [8, 10]. Another problem was determined using ultrasonic scanning and this was the frequency of defects in pallets. These include sound knots, cross grains, decays, holes, and so forth, which account for 30% of total volume overall [5]. Also, another long-term issue with wooden pallets is that of the phytosanitary measures, which require wood packaging materials to adhere to regulations to kill and remove pathogens before usage for sensitive logistics [11]. Metal pallets are also an option, but they involve imposing much higher weights for applications requiring lightweight carrier loading and complete automation. Also, the flexibility factor provided by wood or its reinforced composites is nullified. Manufacturing metal pallets also induces a lot of material waste, which makes the process more cumbersome. The sterilization of metals has become quite difficult in the current scenario, owing to metals' corrosive nature and concerns about chemical spills or inflammable materials [12]. These issues suggest we consider the next best set of materials for pallets, that is, plastics employed at a large scale to compensate for these limitations. Plastic pallets have a longer life cycle and load-bearing capacity than wooden pallets. A major advantage, which is also a major cost-saving factor, is the avoidance of phytosanitary measures for plastics and polymers without compromising the load-bearing capacity. The special feature that plastic provides is its recyclability and reusability. Plastic pallets are manufactured using injection moulding, and the overburn may harm the final pallet. To avoid this, manufacturers also add fire retardants like deca/hexabromide and its derivatives, which also attenuate the toxicity of the final product [11]. With the rise of additive manufacturing, our study explores alternative solutions to pallet manufacturing, refraining from the toxic nature, weight factor ratio to be maintained,

resistance to chemical reaction, and ensuing imperceptible corrosion factor [11, 12]. To the best of the authors' knowledge, negligible work has been carried out in the additive manufacturing domain for making specialized pallets and remains largely unexplored. With work done in fused deposition modelling of pallets gaining traction and general acceptance of making polymer pallets, a wide domain of alternative techniques remains to be explored [12]. In this work, specialized pallets are manufactured, making use of digital light processing (DLP) and stereolithography (SLA) and environmentally sustainable materials to ensure innovative "green" low carbon dioxide-emitting manufacturing technology processes. Furthermore, these pallets undergo static analysis for disparate loading conditions, and are further subjected to various analyses in the form of detailed surface characterization to comprehend the need and applications in correlation to the traditional cycle.

1.1. Pallet making: additive manufacturing technique

Additive manufacturing is a layer-by-layer addition of material formed by extracting the information from the digital computer-aided design (CAD) model. The CAD model is constructed and then is converted into slices (layers) by the slicer software and printed in slices, as each layer is built on the additive bed. Various additive manufacturing techniques are employed for a variety of materials and requirements, VAT polymerization refers to a technique wherein a vat of liquid photopolymer resin is used to construct the model layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required. Other additive manufacturing technologies include material extrusion, material jetting, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition. Because our research on pallets is limited to the use of plastic for specialized applications, we have limited our work to focus on stereolithography (SLA) and digital light processing (DLP), both of which are subderivatives of the VAT polymerization technique.

1.2. Stereolithography

The first additive manufacturing process was introduced in the 1980s, utilizing the ability of ultraviolet (UV) and laser light sources to cure the polymers. This process works on the vat polymerization technology with raw material about photo-curable resin. SLA, widely considered to be an accurate process for building 3D objects, has its limitations, because the build process and the laser source are point-based methods, which makes SLA slower in terms of printing time. With the advent of additive manufacturing, researchers' interest SLA has been elevated because of the customized solution requirements, with the effect of the time factor receding. Anil et al. [12] attempted 3D printed pallets, which applied a cross-hatched design to increase the capacity of the shear factor owing to the length of the span in correlation with rectilinear fill. Researchers [13] provided a review study on stereolithography, in which medical imagery and complex surgery procedures could be enhanced with stereolithography-printed biomedical devices. With further enhancement, stereolithography was used for intravesical drug delivery in terms of flexible printed parts leading to good blood compatibility [14]. The constitution of an elastoplastic model [15] described the mechanical behaviour of the SLA-printed parts, forming initial study approach for load carriers and storage shelves in the mechanical industrial field. Furthermore, another study made use of numerical modelling to predict the elastic properties of green SLA parts of an alumina suspension for structural applications [16]. With disparate applications from wide domains, SLA-type additive manufacturing bolsters provide case-to-case solutions, especially in printing pallets for specialized packaging and logistics operations.

1.3. Digital light processing

The process is governed by curing the raw material with UV or laser light, and the major standout in correlation with other VAT polymerization techniques lies in the fact that the DLP process involves area scanning, which tends to speed up the process and thereby reduces the time to build

parts. The raw material for DLP is a photo-curable resin which acquires the required shape based on the input CAD geometry. Once the CAD geometry is converted to 2D slices in the slicing software, this process projects the 2D slice on the resin like a light projected on a projector screen and cures it based on the required parameters [17]. This process cures the resin using the pixel configuration to exploit the geometric details of the CAD part. With the modern customized solution requirements, this process is attracting much interest among researchers. It was depicted that the curing behaviour of the photopolymers availing DLP profoundly affected the reduction of the secondary UV process and enhanced the hardness and strength of the final part [18]. With advancements, DLP has been applied in the medical field in the process of creating bone implants [17], as well as in formation of self-healing hydrogels [18] attenuating strength by 72%, soft robotics (grippers) [19], energy storage [20], plastic moulds, and pallet making [20, 21].

1.4. Significance distinction of DLP and SLA

Although both processes are classified under VAT polymerization, a thorough distinction exists between them, with layer curing either in the presence of an external light source or laser [12, 17]. With the prevalent condition of area scanning (pixel configurations), as depicted in Figure 1, the DLP process can complete the build process faster than the point-based method in SLA.

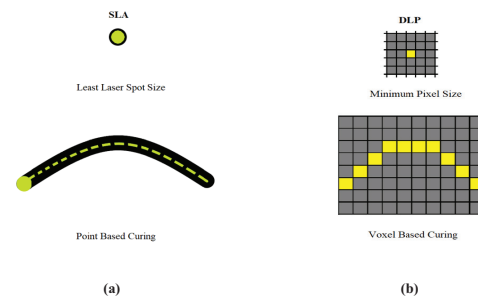
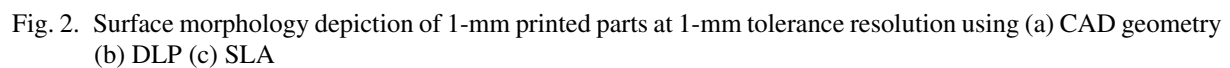


Fig. 1. Depiction of printing (a) SLA: point-based approach; (b) DLP: area scanning



Given the advancements occurring in the area of 3D printing in correlation with VAT polymerization techniques, a comprehensive evaluation of pallet formation must be performed for specialized transportation of high-risk goods: defence sectors; modular closing of aerospace parts during transportation; support structures for long, slender ratio parts as was done for the age-old enervation

models made of wood (moisture absorption; reaction with chemicals; environmentally susceptible); aluminium (cost factor surge, heavy load factor of the pallet alone, mediocre impact strength) fall short for complex parts and delicate sectors. There has been limited work carried out in the area, so the authors in this work showcase the modelling of pallets to defined standards, using both SLA and DLP models. The capabilities for each are to be evaluated along with the performance of their basic simulation, through mechanical tests and surface analysis in comparison with each other. The parameters for performing various physical tests and evaluating their chemical attributes, coupons are built using layer thickness and alternative materials as parameters corresponding to tensile strength, elongation, and hardness corresponding to the levels of experiments for each VAT polymerization process. The common vector plane response variables were analysed using a hybrid AHP-TOPSIS (analytic hierarchy process and technique for order of preference by similarity to ideal solution) statistical method for individual methods to reach a solution as close as possible to the ideal solution in the experimental runs conducted. This run is utilized to print a prototype of a four-way pallet based on ISO Standard MH-2016-1 on either of the processes. Simulations are also carried out to check for the material's stability under disparate loading conditions encountered in the industrial setting—additionally, morphological characteristics should orient the surface characteristics in regard to our applications.

The range of types of pallets often employed in the industry include four-way pallets, block pallets, stinger pallets, panel decks, and so on. The idea is to check initially for how capable the process is regarding mechanical compatibility. As aforementioned, the processes considered for checking the compatibility in additive manufacturing are SLA and DLP, for which we have considered two process parameters: layer thickness and disparate proprietary materials. For this iteration, we will employ an L9 orthogonal array to develop experimental runs. The 3D printing is based on these experimental runs, and mechanical testing is performed to determine the response variables.

The response variables considered were tensile strength, percentage of elongation, and shore hardness. The AHP-TOPSIS method optimizes these response variables to develop close-to-ideal solutions in the experimental runs. Having a close-to-ideal solution, a model comprising a four-way pallet is 3D printed, using DLP and FDM, based on ISO standards.

2. Materials and methods

2.1. Process/parameters for printing of pallets—SLA

Form labs SLA printer [21] was employed for printing the pallet samples on the basis of tensile test requirements for mechanical analysis. Table 1 depicts the process parameter values for building the test coupons.

The process parameters under consideration are layer thickness, which are 25 μ , 50 μ , and 100 μ , and co-polymer inks, which are industrial-grade Grey V4, Clear V2, and Model V3. These materials are bio-compatible, nonreactive and toxic, thereby holding strong to the application of transporting high-value chemical goods without any surge effect due to spillage/leaks or disturbances during transport. The industrial grade material properties are listed in Table 2.

Table 1. Process parameters corresponding to SLA 3D printing of pallet coupons

Layer Thickness (μ m)	Material
25	Gray V4
50	Model V3
100	Clear V4

Table 2. Material properties of the industry grade pallet 3D printing materials—SLA

Materials	Grey V4	Model V2	Clear V2
Tensile strength (MPa)	65	42	65
Percentage of elongation	6.2	4.8	6.2
Izod notched impact (J/m)	25	24	25
Heat deflection temperature ($^{\circ}$ C)	73.1	75	73.1

Table 3. Orthogonal L₉ array experimental runs for SLA 3D printing of pallet coupons

Experimental runs	Layer thickness	Material
1	25	Gray V4
2	25	Clear v4
3	25	Model V2
4	50	Gray V4
5	50	Clear
6	50	Model V2
7	100	Gray V4
8	100	Clear
9	100	Model V2

Table 4. Process parameters corresponding to DLP 3D printing of pallet coupons

Layer thickness (μm)	Material
30	FlexBlack-20
40	ToughBlack-20
50	ProBlack-10

To ensure that uniformity is obtained in the analysis method and also to keep the cost factor of printing low, a L₉ orthogonal array experimental design was considered for process parameters [22–24] as indicated in Table 3, and the number of repetitions for each sample is five.

2.2. Process/parameters for printing of pallets—DLP

The DLP method uses the area scanning method, for which a standalone [25] 3D system printer was availed for printing of pallets and coupons related to pallet making. The process parameters for DLP 3D printing of pallets are layer thicknesses of 30 μ , 40 μ , and 50 μ , and industry standard materials, comprising FlexBlack-20, ToughBlack-20, and ProBlack-10, as indicated in Table 4.

The industry standard material properties used for 3D printing of pallets using DLP are as indicated in Table 5.

To ensure uniformity, overall rapid analysis method, and also to keep the cost factor of printing low, an L₉ orthogonal array design of experiments was considered for process parameters as indicated in Table 6, and the number of repetitions for each

Table 5. Material properties of the industry grade pallet 3D printing materials—DLP

Materials	Flex BLK-20	Tough BLK-20	Pro BLK-10
Tensile strength (MPa)	35	42	56
Percentage of elongation	71	27	12
Izod notched impact (J/m)	105	35	22
Heat deflection temperature ($^{\circ}\text{C}$)	41	55	70

Table 6. Orthogonal L₉ array experimental runs for DLP 3D printing of pallet coupons

Experimental runs	Layer thickness	Material
1	30	FlexBLK-20
2	30	ToughBLK-20
3	30	ProBLK-10
4	40	ToughBLK-20
5	40	ProBLK-10
6	40	FlexBLK-20
7	50	ProBLK-10
8	50	FlexBLK-20
9	50	ToughBLK-20

sample is five in numbers [21–23] corresponding to the experimental work.

Static simulations are also carried out to check for the material's ability in disparate loading conditions in the industrial regime. Furthermore, morphological characterization comprising SEM (surface structural attributes), AFM (waviness factor), and XRD (residual stress factor) is carried out in correlation with each printing condition to evaluate the entire model of pallet application.

2.3. 3D printing of standard pallet test coupons

To analyse the tensile mechanical characteristics of the printed parts, coupons were designed based on ASTM D638, as per standard for plastic materials. The major drawback pertaining to additive manufacturing was lack of specific standards for comparison, therefore, ASTM D638 as depicted in Figure 3, was considered for benchmarking.

The type IV CAD model was developed using the Creo tool and was formatted into a .stl file

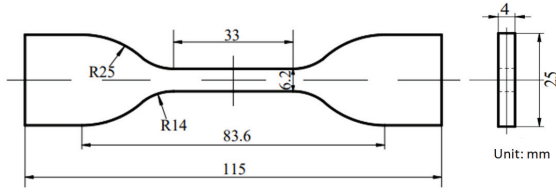


Fig. 3. SLA and DLP 3D printing of tensile specimen dimensions: ASTM D638

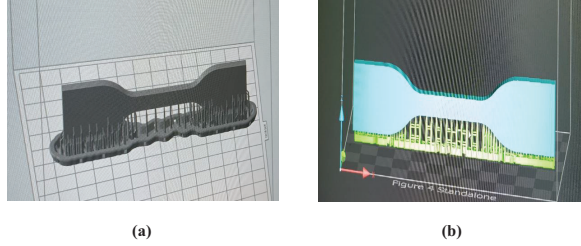


Fig. 4. GUI type IV tensile specimen (a) Preform: SLA, (b) 3D sprint: DLP software

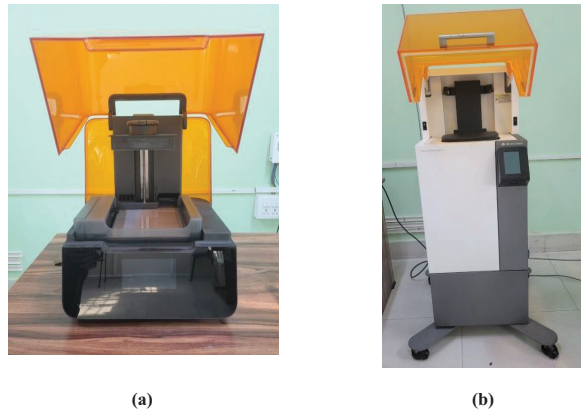


Fig. 5. 3D printing of coupons (a) SLA Form 3 (b) DLP Figure 4 Standalone (CITD additive lab facility, MSME Tool room facility, Hyderabad, Govt. of India)

for 2D slicing software (perform for SLA; and 3D sprint for DLP), for optimal guidance and assistance (GUI) for carrying out the printing operation as depicted in Figure 4.

As per the requirements, the tensile coupons for both SLA and DLP are 3D printed as per the ASTM standard, using the machines as indicated in Figure 5. The 3D printing machine's salient features are detailed in Table 7.

Table 7. 3D printing machine details: SLA – Form 3 and DLP

Machine Name	Form labs 3	Machine Name	DLP Standalone System
Build Volume	145 × 145 × 185 cc	Build Volume	124.8 × 70.2 × 196 cc
Resolution	25 μ	Resolution	1920 × 1080
Laser power	250 mW	Wavelength	405 nm
Laser Spot size	85 μ	Pixel pitch	65 μ



Fig. 6. Bottom-up approach 3D printing of pallet coupons in DLP method

For DLP printing, the GUI interface verification adds a constructive nature, as it is a bottom-up approach, that is, material upside down printing pertaining to constraint of support structures, as depicted in Figure 6.

The pallet tensile coupons are printed in accordance with L_9 orthogonal array experiment as listed in Table 3 and Table 6 for SLA and DLP, respectively.

In commercial applications of load lifting or transportation application, pallets are manufactured, using injection moulding, which falls under the area of subtractive manufacturing. Though these pallets are used for mass production any specialized applications introduce a limiting factor, especially those that involve biomedical samples delicate aero components, thus causing a major impact from product design development to the lead time effect as the entire design and manufacturing process takes a hit. Making a die for production in large numbers also involves steps in subtractive methods, starting from rough milling,

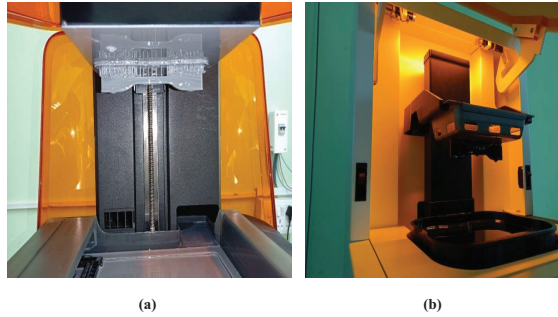


Fig. 7. 3D printed ASTM D638 type IV pallet coupon using (a) SLA process: form 3 printer (b) DLP method: stand-alone printer

CNC machining, jig boring, die sink EDM, surface grinding, and assembly components. This eliminates specialized applications requiring an alternative method, especially for wide-scale transportation issues, as the focus lies on pallets. To recreate a real-time model, a benchmark comparison is carried out to study the mechanical characteristics of general injection moulded pallet material acrylonitrile butadiene styrene (ABS) in correlation to SLA and DLP printed pallets. The complete required die, and the manufacturing of a pallet according to an ASTM tensile coupon specimen as per commercial replicator is carried out in Central Institute of Tool Design (CITD), Hyderabad, by two-plate hand mould die with a single cavity. It is possible to execute the whole setup of making a die, to completion by injection moulding is carried out in the facilities available in CITD, Hyderabad adhering to industrial requirements as depicted in Figure 8.

2.4. Uniaxial tensile test

The uniaxial tensile test is a destructive process that indicates information about the yield and tensile strength and measures the forces that would cause a plastic specimen to break. ASTM D638 type IV specimen 3D printed pallet specimen coupons were evaluated, using Instron model 5966, as depicted in Figure 9. The range of the machine is 0–10 kN, having a minimum and maximum speed of 0.001 mm/min and 1500 mm/min, respectively. The requisite pallet coupon specimens are placed in a universal testing machine with the aid of grippers,

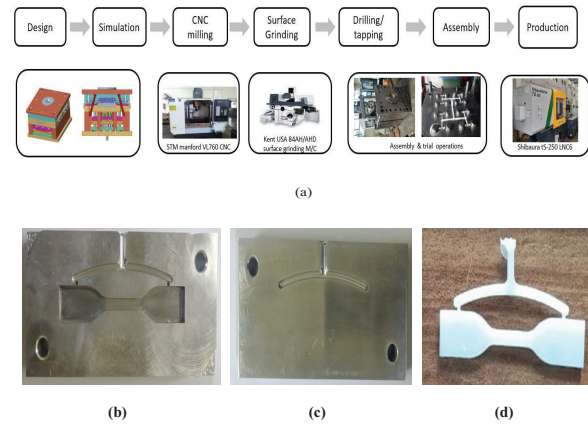


Fig. 8. (a) Complete process for developing a commercial pallet tensile coupon replicator (CITD, Hyderabad facilities); (b) bottom half; (c) top half of injection mould die; (d) ABS pallet tensile specimen coupon prepared with gate and runner

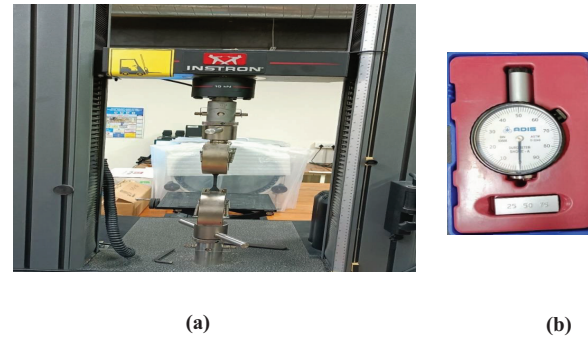


Fig. 9. Investigation of (a) uniaxial tensile test of SLA and DLP 3D printed ASTM D638 type IV samples; machine used: Instron 5966 model, (b) Shore A hardness durometer

with a gradual load being applied to the specimens until the failure or snap region is reached. This point is dependent on the polymer conditions for which the resultant tensile loads are recorded for individual 3D printed specimens printed under SLA and DLP conditions.

In order to ensure precise uniaxial testing, specimens were marked with vertical gauges for clamping. To avoid slack from the load string for the clamping load, preload of 2N was provided to avoid uncertainty in a testing factor. The factors considered for conducting the test were approximately a load cell of 10 kN and a load rate

Table 8. Response variables for SLA 3D-printed pallet specimens

Experiment No.	Layer thickness (μm)	Material	Tensile strength (MPa)	Elongation in (%)	Hardness (Shore D)
1	25	Grey V4	65.00	6	50.00
2	25	Clear V4	63.05	5.87	48.50
3	25	Model V2	61.00	5	55.00
4	50	Grey V4	61.55	5.85	85.00
5	50	Clear V4	61.40	5.733	82.45
6	50	Model V2	59.48	4.89	53.35
7	100	Grey V4	61.43	5.67	47.50
8	100	Clear V4	59.97	5.59	80.75
9	100	Model V2	58.98	4.67	52.25

Table 9. Response variables for DLP 3D-printed pallet specimens

Experiment No.	Layer thickness (μm)	Material	Tensile strength (MPa)	Elongation (%)	Hardness (Shore D)
1	30	FlexBLK-20	33.25	71.25	68.75
2	30	ToughBLK-20	41.75	28.50	77.00
3	30	ProBLK-10	56.05	11.4	75.53
4	40	ToughBLK-20	40.50	27.65	74.69
5	40	ProBLK-10	57.23	11.64	77.12
6	40	FlexBLK-20	32.25	69.11	66.69
7	50	ProBLK-10	57.34	12	79.50
8	50	FlexBLK-20	31.59	67.69	65.31
9	50	ToughBLK-20	39.66	27.08	73.15

of 5 mm/min [26, 27]. Upon breakage or snap of the polymer material, the test is automatically completed, and the results corresponding to each orthogonal array experiment for SLA and DLP were recorded accordingly. For polymer materials, the notable observation would be in the variation of tensile strength and the percentage of elongation at the breakage region and these have been tabulated in Table 8 and Table 9 for the pallet specimens corresponding to SLA and DLP, respectively.

2.5. Hardness testing

The pallets undergo heavy loading, and thereby the hardness of the pallet specimens plays a key role in determining the load factor because the material should possess high toughness for load-carrying capacity but should not be too brittle, which would lead to fractured, uncontrollable failure. For polymers, a shore D hardness scale durometer was used as indicated in Figure 9, as per the ASTM D2240 standard to measure the resistance

to permanent deformation. The dial durometer involved pressing the indenter into the surface to capture the hardness value of the specimen at five different points, for which the average reading was tabulated for SLA and DLP pallet specimens, and the measurement has been tabulated in Table 8 and Table 9, respectively.

2.6. Optimising the process parameters using MCDM technique

With preliminary experiments conducted for SLA and DLP, a common vector plane for a close to ideal solution must be obtained for correlation between values. For this, multicriteria decision-making methods (MCDM) were adopted, which provided decrement in statistical variability and close to a common vector plane through decision ranking. The methods VIKOR, WSM, TOPSIS, ELECTRE, DEMATEAL, MOORA, and others form different techniques that are widely adopted for solving and finding the Euclidean distance from

the common vector plane [22–24, 26, 27]. For comparing and inferring a statistically close to ideal vector value, SLA and DLP, a hybrid AHP-TOPSIS methodology was adopted to find the set of optimized parameters.

2.7. Analytical hierarchy process

The analytical hierarchy process (AHP) involves the decision-maker's expertise to develop quantitative judgements on multicriteria evaluation. The process is based on a priority basis, categorizing attributes based on their 1 to 9 scale [30]. The multiple attributes for a complex problem are broken down into systematic hierarchical procedures to ensure low complexity and faster solutions for attributes and responses [28]. In our study, AHP was employed as a pairwise matrix comparison to come up with the weights computation, which is then utilized as a weighing criterion for response variables to optimize for closeness to the ideal solution. The AHP table formulated for our three response variables corresponding to pairwise and weights are tabulated in Tables 10 and 11.

After computing the weights for the response variables, the method was evaluated for consistency ratio. The consistency ratio was 0.081, less than 0.1, satisfying the AHP pairwise matrix usage criteria [30]. Thus, the current sets of weights were employed for hybrid analysis with the statistical TOPSIS method. For linear consistency, the same weights for data correspond to 3D-printed pallets for SLA and DLP methods, respectively.

Table 10. AHP pairwise computation matrix

Attributes	Tensile strength	% Elongation	Hardness
Tensile strength	1.00	5.00	4.00
% Elongation	0.20	1.00	2.00
Hardness	0.25	0.50	1.00

Table 11. Weights disguised for each response variable

Variable	Weight
Tensile strength	0.687
% Elongation	0.186
Hardness	0.127

2.8. TOPSIS methodology

The TOPSIS method computes the solution for the closeness to the ideal solution. The technique for order preference by similarity to the ideal solution (TOPSIS) caters for the best alternative, which has the shortest Euclidean distance from the ideal solution and is farthest from the negative ideal solution [29]. This method adopts normalising the attributes for uniformity in computing the Euclidean distances for closeness to the ideal solution. The steps involved in TOPSIS are as follows:

- Step 1:** The decision matrix is disguised based on the response variables.
- Step 2:** The decision matrix is normalised for uniformity of process computation. There are numerous ways of normalisation, i.e., vector normalisation, averaged normalisation, min-max normalisation, and so forth. For ease of adaption and faster calculation, vector normalisation has been adapted to get the normalised decision matrix.
- Step 3:** This normalised decision matrix is then computed with the weighing criteria for each response variable. To integrate the AHP technique, the weighing criteria from Table 11 have been adapted to obtain a weighted, normalised decision matrix.
- Step 4:** The weighted, normalised decision matrix is then utilised for computing Euclidean distance for closeness to the ideal solution.
- Step 5:** The closeness coefficient is computed and ranked to find the alternatives close to the best solution.

The hybrid AHP-TOPSIS evaluation is tabulated in Tables 12 and 13 for SLA and DLP, respectively.

Based on the adaption of the hybrid method AHP-TOPSIS, the corresponding close-to-ideal values for SLA were 50 μ layer thickness and Grey V4 material correspondence. Similarly, the most optimised alternative close to the ideal solution for DLP was 50 μ layer thickness and ProBLK-10 material. The optimised vector plane for 3D printed

Table 12. AHP-TOPSIS methodology for 3D printed pallets using the SLA process

S. No.	Layer thickness (μm)	Material	Weighted matrix			Closeness to ideal solution		Closeness coefficient Pi	Rank
			W_TS	W_%E	W_H	Si+	Si-		
1	25	Grey V4	0.24	0.07	0.03	0.02	0.16	0.87	4
2	25	Clear v4	0.24	0.07	0.03	0.03	0.16	0.86	5
3	25	Model V2	0.23	0.06	0.04	0.03	0.17	0.86	6
4	50	Grey V4	0.23	0.07	0.06	0.01	0.16	0.92	1
5	50	Clear	0.23	0.06	0.06	0.01	0.16	0.92	2
6	50	Model V2	0.22	0.06	0.04	0.03	0.17	0.84	8
7	100	Grey V4	0.23	0.06	0.03	0.03	0.16	0.85	7
8	100	Clear	0.22	0.06	0.05	0.02	0.16	0.89	3
9	100	Model V2	0.22	0.05	0.03	0.03	0.17	0.83	9

Table 13. AHP-TOPSIS method for 3D printed pallets using DLP method

S. no.	Layer thickness (μm)	Material	Weighted matrix			Closeness to ideal solution		Closeness coefficient Pi	Rank
			W_TS	W_%E	W_H	Si+	Si-		
1	30	FlexBLK-20	0.17	0.10	0.04	0.12	0.09	0.41	4
2	30	ToughBLK-20	0.22	0.04	0.04	0.10	0.06	0.37	7
3	30	ProBLK-10	0.29	0.02	0.04	0.09	0.13	0.60	3
4	40	ToughBLK-20	0.21	0.04	0.04	0.11	0.05	0.33	8
5	40	ProBLK-10	0.29	0.02	0.04	0.08	0.13	0.61	2
6	40	FlexBLK-20	0.17	0.10	0.04	0.13	0.08	0.39	5
7	50	ProBLK-10	0.30	0.02	0.05	0.08	0.13	0.61	1
8	50	FlexBLK-20	0.16	0.10	0.04	0.13	0.08	0.38	6
9	50	ToughBLK-20	0.20	0.04	0.04	0.11	0.05	0.30	9

Table 14. Close to ideal solution for SLA and DLP 3D printed pallets: AHP-TOPSIS

Process	Layer thickness (μm)	Material
SLA	50	Grey V4
DLP	50	ProBLK-10

pallets in their respective processes is tabulated in Table 14.

In order to produce optimised alternatives for both processes, the pallet prototypes were printed with a reduced scale of 1:20 in accordance with the ISO standard (MH1-2016), as depicted in Figure 10. The printing process is highlighted in Figure 11.

2.9. Tensile specimen evaluation

Structural analysis is needed in order to evaluate the strength of the decks and compressive strength of the geometries corresponding to pallets and to

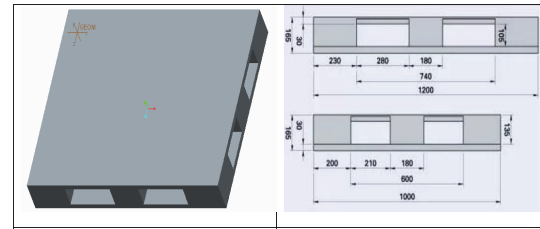


Fig. 10. Design of a four-way pallet as per the ISO MH1-2016 standard in CAD software

estimate the maximum loading capacity the pallets can undertake for a standard set of weights, as its main objective will be in the transportation sector.

2.9.1. Static analysis

Analysis is carried out in static structural analysis mode with one end fixed in ABAQUS software [31]. The tensile specimen is meshed with second-order reduced integration elements (C3D20R). Stress analysis is carried out on the

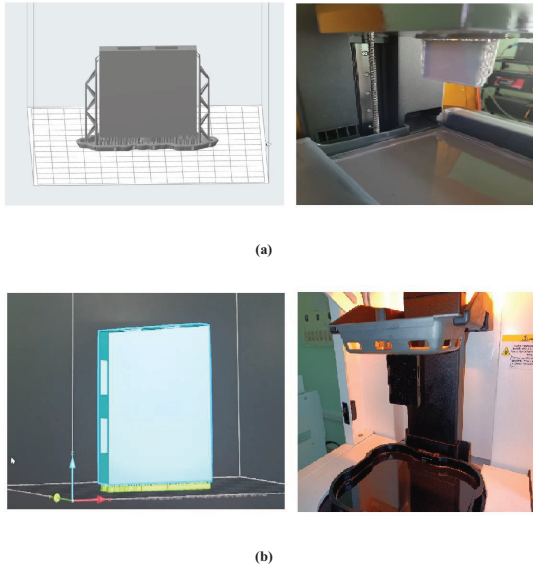


Fig. 11. Pallet 3D printing in accordance with the ISO MH1-2016 standard for optimized values using (a) SLA (b) DLP

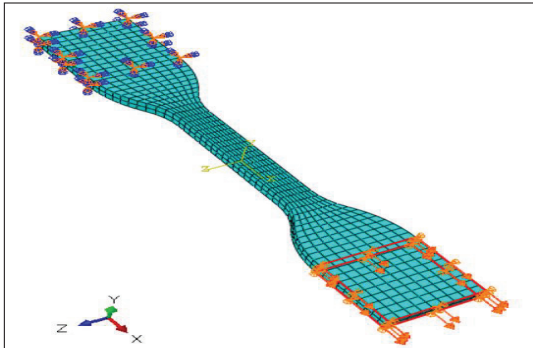


Fig. 12. Finite element model of the ASTM D638 model in ABAQUS 6.14

tensile test specimen with displacement load acting on the other end of the specimen, as per the ASTM D638 standard on Inspiron-5966 in correlation with ABS (commercial replication: injection moulding), Pro-BLK-10 (SLA process), and GrayV4 (DLP method) as depicted in Figure 12.

Input data of materials stress-strain curve is considered from physical data testing after converting true stress-strain data. The displacement and von mises stress values of tensile specimens for injection-moulded and 3D printed materials are evaluated and depicted in Figure 13.

The specimen behaviour is observed in each of the three cases to comprehend the results obtained in the experimental method and to evaluate the maximum stresses and displacement factor corresponding to each case for the 3D printed materials obtained.

An experimental uniaxial tensile test was carried out for 3D-printed (SLA and DLP) pallet samples in comparison with a commercial replicator for a close to ideal solution as indicated in Figure 14.

Gauge length has a colossal stress value when compared to the other regions of the specimen as a result of plastic flow or slippage. Because of the applied load and work done by an external displacement load acting on the specimen, the stress is induced in the specimen after the load application, as indicated in Figure 15, for homogenous object consideration with a constant cross-section and a constant applied load, the total deflection of the object can be determined in terms of P , L , A , and E .

The detailed comparison of simulated versus physical testing for disparate materials for each process are obtained and tabulated in Table 15.

The analytical equation is applied for the tensile specimens as per ASTM standards for given material characteristics of ABS (commercial replication: injection moulding), Pro-BLK-10 (SLA process), and GrayV4 (DLP method). The dimensional change in length is drawn from uniaxial tensile test data for each case and estimated the ratio of change length to original length for strain relation under the region of ultimate tensile strength values. Table 15 and Figure 16 show that the simulation results are ascertained closer to testing and analytical values.

Furthermore, results on the additive manufactured ISO pallet and optimized pallet conditions obtained for each process were also obtained for different loading conditions in the form of rack, fork-lift, floor, and conveyer mode, corresponding to industry applicability.

2.9.2. Pallet simulations

Pallets are generally classified into different categories like block types, stringer pallets, and other models based on usage criteria. Most pallets

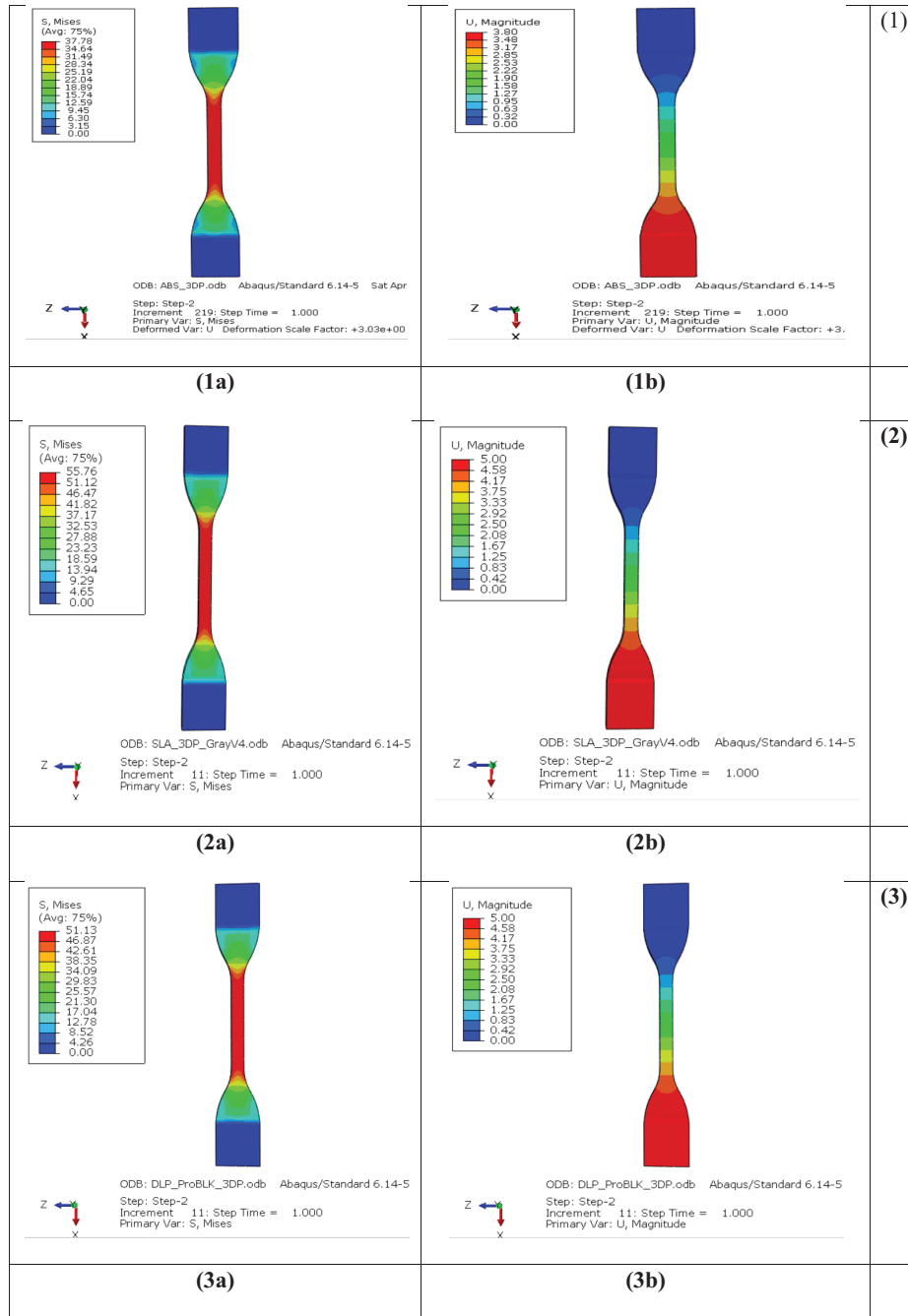


Fig. 13. Simulations of 3D-printed test coupons for pallets corresponding to ABS (commercial replication: injection molding) (1); Pro-BLK-10 (SLA process) (2); and GrayV4 (DLP method) (3) for (a) maximum stress, (b) maximum deformation

experience compressive load in practical usage and transportation. The common major subparts of pallets consist of the top deck, blocks, and bottom deck components. These subparts' quantity and layout will depend on the size and amount of load

transfer. Figure 17 indicates a generic pallet with a full uniform load spread across the pallet.

This work considers coupon levels for deriving the analytical results for displacement and stress values for pallets. The top deck is the part

Table 15. Simulated versus physical uniaxial tensile test for ABS, Pro-BLK, and Grey V4 for injection molding, SLA, and DLP 3D printed samples

Material	Parameter	Simulation	Analytical	Physical testing	Difference between simulation & testing (in %)
ABS	Stress (MPa)	37.78	43.33	40.19	6.37
	Displacement(mm)	1.80	1.88	1.62	10
GrayV4	Stress (MPa)	55.76	57.52	61.55	10.38
	Displacement(mm)	2.89	2.36	3.25	12.45
ProBLK-10	Stress (MPa)	51.31	54.37	57.34	11.75
	Displacement(mm)	2.88	2.69	3.19	10.76

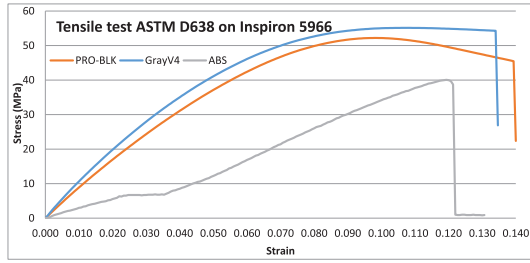


Fig. 14. Experimental uniaxial tensile test results for ABS (commercial replication: injection moulding), Pro-BLK-10 (SLA process), and GrayV4 (DLP method)

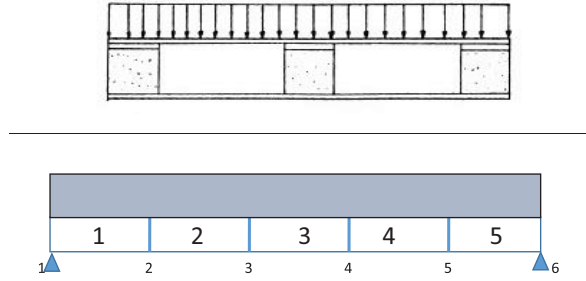


Fig. 17. Coupon pallet 100 mm × 30 mm cross section being considered for (a) side view representing UDL load and (b) top deck of pallet corresponding to five beam elements

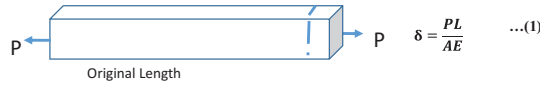


Fig. 15. Prismatic bar with concentrated force

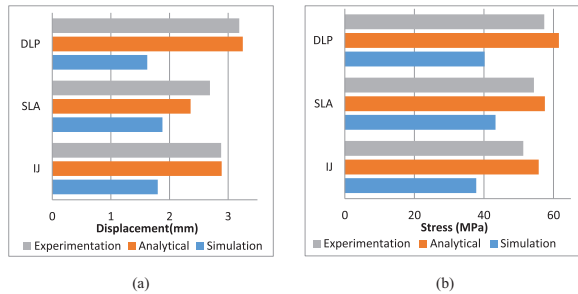


Fig. 16. Simulated, experimental, and analytical uniaxial tensile test results for ABS, Pro-BLK, Grey V4 for injection molding, SLA and DLP 3D printed samples corresponding to (a) deflection (displacement) (b) stress

immediately under the load applied to the pallet, and it is a good choice for finite element analysis using beam elements for a coupon pallet size of

100 mm × 30 mm cross-section using 1D beam elements with five elements and six nodes for a 50-kg load.

In the matrix displacement method, the displacements are considered the unknowns. Each element is represented by its stiffness matrix, which relates the element-end displacements to the element-end forces for the corresponding element. The stiffness matrix for the beam elements representation is provided in Equation (2).

$$F = K * U \quad (2)$$

where F is the local elemental forces; K represents local element stiffness metrics; and U is local displacement of the element. The elemental stiffness matrix of the beam element is indicated in Equation (3).

$$K = \frac{EI}{L^3} \begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} \quad (3)$$

	9.5E+02	9.5E+04	-9.5E+02	9.5E+04	0	0	0	0	0	0	0	0
	9.5E+04	1.3E+07	-9.5E+04	6.3E+06	0	0	0	0	0	0	0	0
	-9.5E+02	-9.5E+04	1.9E+03	0	-9.5E+02	9.5E+04	0	0	0	0	0	0
	9.5E+04	6.3E+06	0	2.5E+07	-9.5E+04	6.3E+06	0	0	0	0	0	0
	0	0	9.5E+02	-9.5E+04	1.9E+03	0	-9.5E+02	9.5E+04	0	0	0	0
	0	0	9.5E+04	6.3E+06	0	2.5E+07	-9.5E+04	6.3E+06	0	0	0	0
	0	0	0	0	-9.5E+02	-9.5E+04	1.9E+03	0	-9.5E+02	9.5E+04	0	0
	0	0	0	0	9.5E+04	6.3E+06	0	2.5E+07	-9.5E+04	6.3E+06	0	0
	0	0	0	0	0	0	-9.5E+02	-9.5E+04	1.9E+03	0	-9.5E+02	9.5E+04
	0	0	0	0	0	0	9.5E+04	6.3E+06	0	2.5E+07	-9.5E+04	6.3E+06
	0	0	0	0	0	0	0	-9.5E+02	-9.5E+04	1.9E+03	0	-9.5E+02
	0	0	0	0	0	0	0	9.5E+04	6.3E+06	0	2.5E+07	-9.5E+04
	0	0	0	0	0	0	0	0	-9.5E+02	-9.5E+04	1.9E+03	0
	0	0	0	0	0	0	0	0	9.5E+04	6.3E+06	0	2.5E+07

Table 16. Simulation and analytical values for displacement for a coupon sample

Parameter	Simulation	Analytical	Difference between (percentage) simulation and analytical
Displacement (mm)	7.29	7.8	6.5

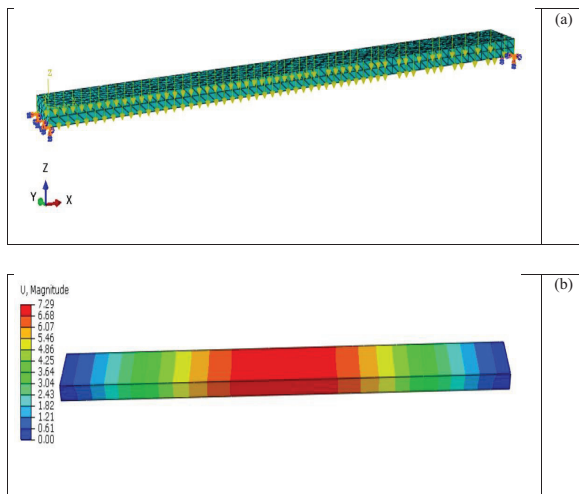


Fig. 19. Beam representation for (a) 3D FEA model with fixed ends, (b) displacement module

The local stiffness matrix for each of the elements is calculated and then summed up into a global stiffness matrix, for which computation is carried out by MATLAB, as represented in Figure 18.

Similarly, the force and displacement matrix is computed with similar iterations. The maximum displacement from the analytical solution is 7.8 mm at the centre of the beam location, for which corresponding 3D FEA simulations are carried out as indicated in Figure 19 and Table 16.

The 3D simulation results for 1/10 of the pallet (coupons) are interlinked closely with 1D analytical calculations using beam element with five elements. The ISO Pallet MH1-2016 and optimized conditions (close to ideal solution) are considered for analysing simulations corresponding to DLP, SLA, and ABS materials.

2.9.3. Analysis of pallets under ISO and optimized conditions: stress and displacement contours

Von mises stress analysis is a widely used engineering tool for predicting material failure under complex loading conditions. In the case of pallet design, Von Mises stress analysis helps identify areas in a pallet where high stresses may exceed the material's yield strength, leading to deformation or failure. Thus, it is imperative to ensure the pallet can withstand the stresses and loads it will face during use [12].

The red region on the von mises stress map indicates areas of high-stress concentration in the pallet. It can be caused by uneven loading, poor design, or material defects. By identifying these areas, designers can modify the pallet design to improve its strength and durability, such as adding reinforcement or altering the shape to reduce stress concentrations [9, 12–14].

The application of Von Mises stress analysis can be highly beneficial in pallet design to enhance the pallet's performance, safety, and longevity. Careful consideration of high-stress areas on the stress map is a critical step in the design process. By optimizing the design of the pallet using von mises stress analysis, the risk of material failure and the associated economic and environmental impacts can be reduced. Therefore, incorporating von mises stress analysis into the pallet design process is a crucial aspect that must be considered [12, 15].

The displacement contour is a visual representation of the deformation that occurs in a structure when subjected to external loads. This tool is widely used to analyse the structural response of a component or system under varying loading

conditions and helps identify areas of high-stress concentration and potential failure [17].

The displacement contour is generated through a finite element analysis process, which involves dividing the structure into a mesh of discrete elements and applying elasticity equations to calculate the deformation of each element in response to the load. The resulting displacement is plotted at each point in the structure to generate the displacement contour [12–15].

The information the displacement contour provides is crucial for optimizing the structure's design to improve its performance and prevent failure. For example, engineers can identify areas of the structure that experience high-stress concentrations and modify the shape, size, or material properties accordingly [9, 12, 15].

2.9.4. ISO pallet 3D simulation

ABAQUS simulates real-life loading situations to understand the material strength and load-withstanding capacity. The disparate loading conditions availed in the study of the designed pallets are uniformly distributed flexible loads, rigid loads, rigid line loads, point loads, and discrete loads, a range that allows simulation of a real-time situation on the actual weight-carrying pallets. For the analysis of designed pallets, a uniformly distributed load of 1000 kg is used for this range of supports.

The boundary conditions used in analysing a pallet design are selected, representing floor, forklift, rack, and conveyor support, as indicated in Figure 20. The pallet meshes with first-order reduced integration elements (C3D8R) for the static simulation, as indicated in Figure 21.

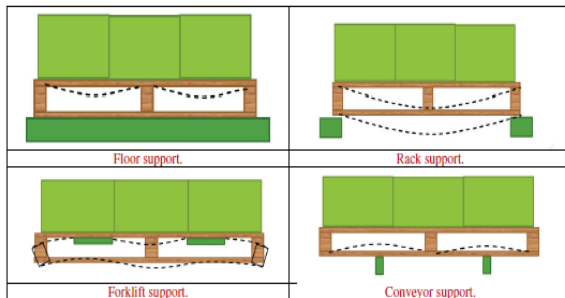


Fig. 20. Basis of boundary conditions for pallet analysis

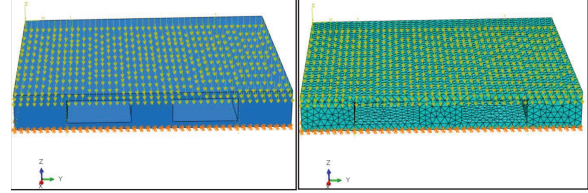


Fig. 21. ISO Pallet CAD model and finite element model with load distribution

Deflection and von mises stress values for the ISO pallet standard are analysed and the values are depicted in Figures 22, 23, and 24 for ABS, SLA, and DLP material, respectively.

It has been observed that the deflections and von mises stress values for the ISO pallet standard are lowest in floor support in comparison with rack, forklift, and conveyor supports, as indicated in Figure 25.

The von mises stress was analysed for all the cases subjected to pallet simulation for the ISO model. The red region, as depicted, indicates a vast amount of loading factor and maximum displacement region when the load is applied to the pallet [12].

With an increase in displacement and stress values in rack support in comparison to floor, forklift, and conveyor, a detailed comparison of the same is carried out separately for DLP and SLA, as tabulated in Table 17, Figure 26 and Table 18, and Figure 27, respectively, indicating a lower deflection in DLP condition, owing to area scanning parameters, thereby having an inherent toughness value [12, 16].

2.9.5. Optimized pallet 3D simulations

A simulation is carried out for optimized design conditions with a lower material reduction, for real-life loading situations in order to understand the material strength and load-withstanding capacity. The loading conditions used in this study are uniformly distributed flexible loads, uniformly distributed rigid loads, rigid line loads, point loads, and discrete loads on the actual product. For the analysis of designed pallets, a uniformly distributed load of 1000 kg is used for disparate supports.

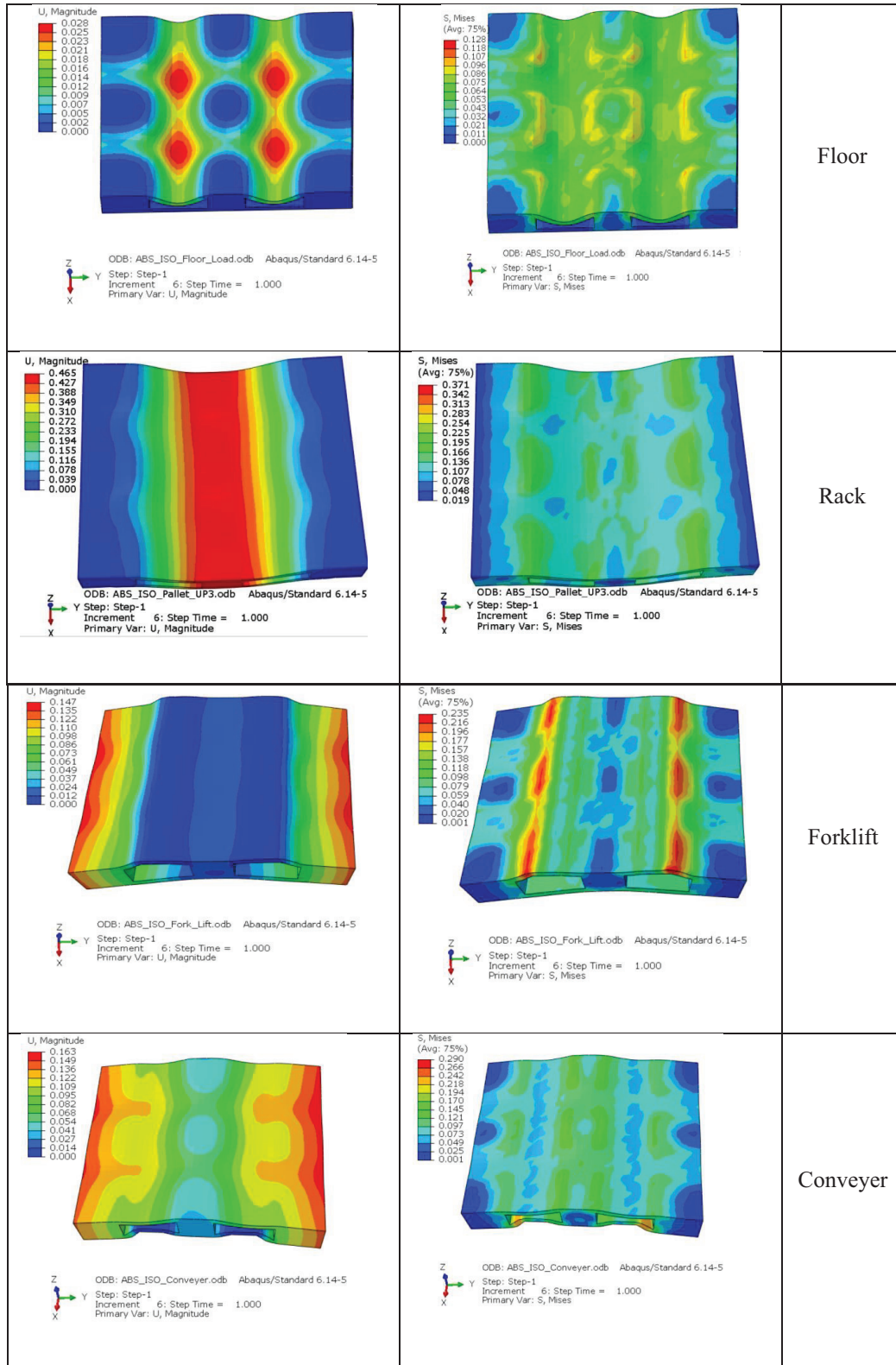


Fig. 22. Displacement and stress contours: ISO pallet corresponding to ABS material

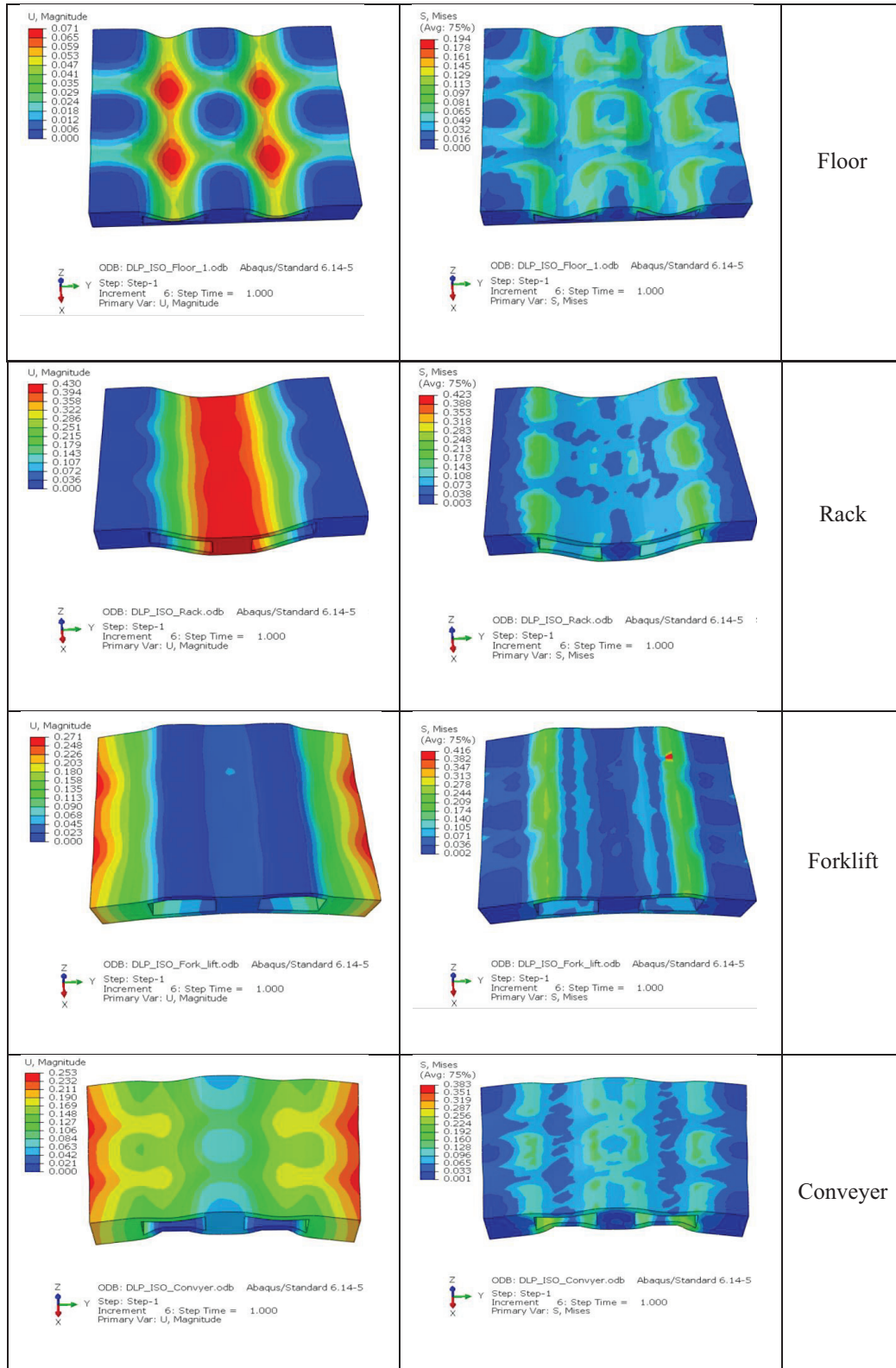


Fig. 23. Displacement and stress contours: ISO pallet corresponding to DLP material

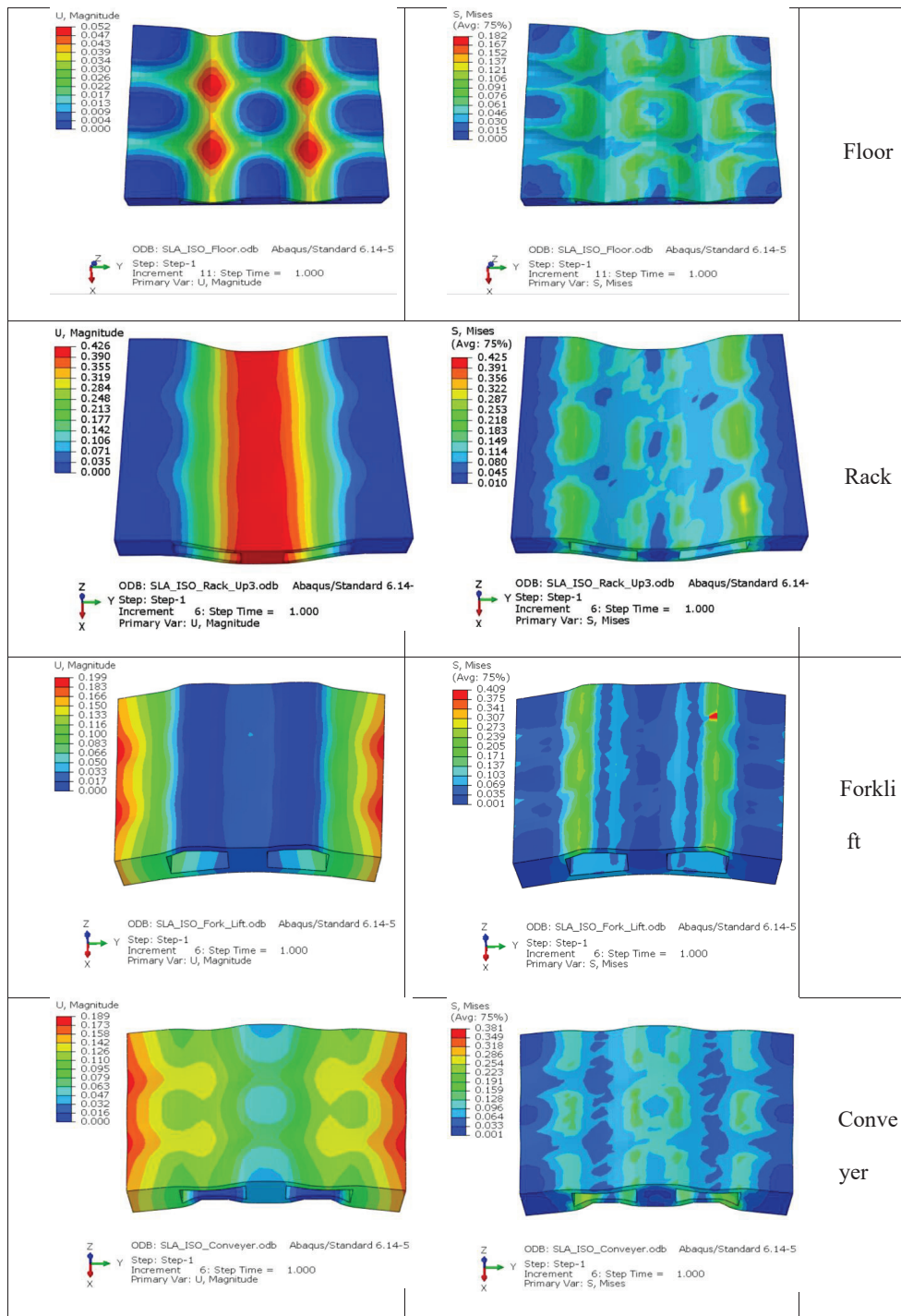


Fig. 24. Displacement and stress contour: ISO pallet corresponding to SLA material

The boundary conditions used in analysing a pallet design are selected, similar to the ISO pallet design, and corresponding to the floor, forklift, rack, and conveyor support, as indicated in Figure 20, but with a wide reduction in material consumption, thereby increasing

Table 17. Comparison of rack support vs. floor support, rack support vs. forklift support, and rack support vs. conveyor support for DLP

Comparison for deflection			Comparison for von mises stress		
Rack vs. floor	Rack vs. forklift	Rack vs. conveyor	Rack vs. floor	Rack vs. forklift	Rack vs. conveyor
83.49	36.98	41.16	54.14	1.66	9.46
83.50	37.06	41.12	54.12	1.55	9.54
83.52	36.87	41.06	54.39	1.70	9.63
83.54	36.96	40.99	54.40	1.57	9.75
83.57	37.06	40.91	54.42	1.77	9.54
83.67	37.05	41.04	54.44	1.61	9.68
83.72	37.21	40.93	54.46	1.88	9.86
83.80	36.87	40.78	54.49	2.25	10.11
83.22	37.06	41.26	54.55	2.10	10.49
83.18	36.45	41.12	54.63	2.78	11.11
83.33	37.50	41.67	56.16	2.74	10.96
83.33	36.11	41.67	57.90	5.26	13.16

Table 18. Comparison of rack support vs. floor support, rack support vs. forklift support, and rack support vs. conveyor support for SLA

Comparison for deflection			Comparison for von mises stress		
Rack vs. floor	Rack vs. forklift	Rack vs. conveyor	Rack vs. floor	Rack vs. forklift	Rack vs. conveyor
87.79	53.29	55.63	57.18	3.76	10.35
87.95	53.08	55.64	57.29	4.09	10.74
87.89	53.24	55.49	57.30	4.21	10.67
87.77	52.98	55.49	57.45	4.66	11.18
88.03	53.17	55.63	57.84	4.88	11.50
87.90	53.23	55.65	58.10	5.53	11.86
87.79	53.05	55.40	58.26	5.96	12.39
87.57	53.11	55.37	58.47	6.56	13.11
88.03	53.52	55.63	59.06	8.05	14.09
87.74	52.83	55.66	59.65	9.65	15.79
87.32	53.52	54.93	62.50	13.75	20.00
88.57	51.43	54.29	66.67	22.22	26.67

the economic factor. The pallet is meshed with first-order reduced integration elements (C3D8R) for the static simulation, as indicated in Figure 28.

Deflection and von mises stress values for optimized pallet condition are analysed and the values are depicted in Figures 29, 30, and 31 for ABS, SLA, and DLP material respectively.

It has been observed that the deflections and von mises stress values for optimized pallet conditions are at their highest in floor followed by forklift support in comparison with rack and conveyor supports, as indicated in Figure 32.

The von mises stress was analysed for all cases of the optimized pallet, and the red region in

the figures indicates where the highest load is experienced during uniform loading. This analysis provides engineers with valuable insights into the structural response of the pallet to applied loads and helps identify potential failure areas, which can inform design modifications to improve performance and prevent failure [12, 15].

With an increase in deflection and stress values in rack support in comparison to floor, forklift, and conveyor, a detailed comparison of the same is carried out separately for DLP and SLA processes for optimized conditions, as tabulated in Table 19, Figure 33, and Table 20, Figure 34, respectively, indicating lower deflection and stress

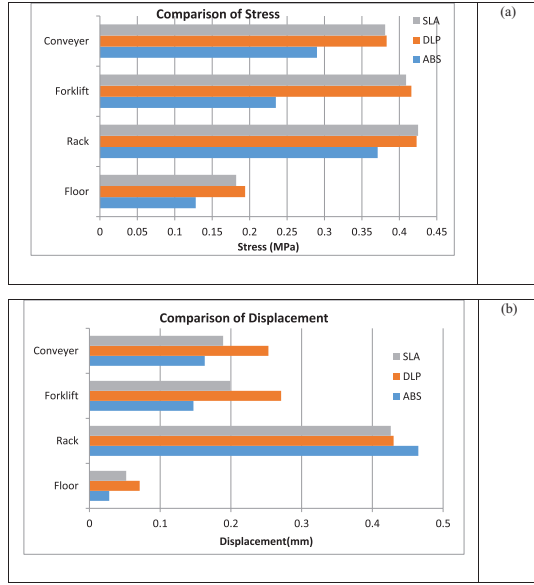


Fig. 25. Comparisons of (a) von mises stress and (b) displacement on the basis of pallet supports

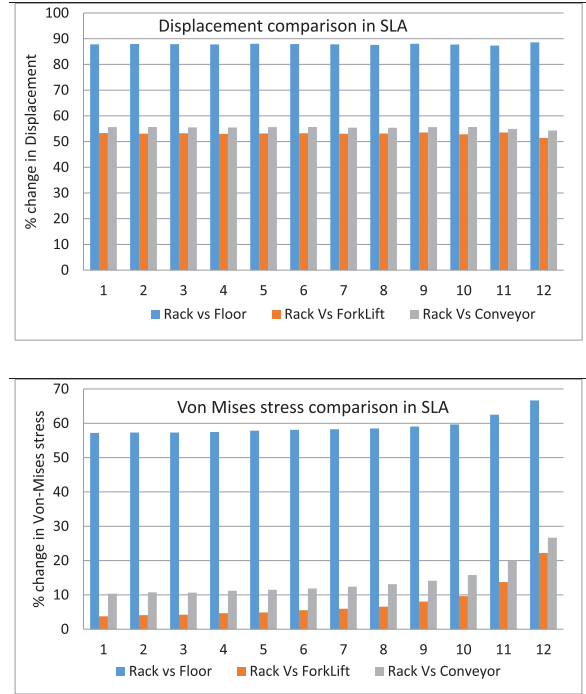


Fig. 27. Comparisons of deflection and von mises stresses for SLA manufactured pallet



Fig. 26. Comparisons of deflection and stresses for DLP-manufactured pallet

contours in the DLP condition, owing to the area-scanning parameter, thereby having inherent toughness value [12, 16].

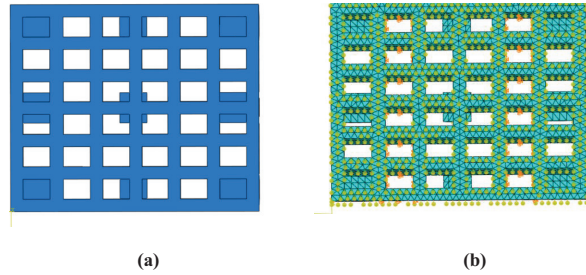


Fig. 28. (a) CAD model (b) Finite element model for optimized pallet design

2.9.6. Morphological analysis

Surface morphology

The surface material of the pallet in both conditions is made by availing biodegradable polymers like ProBLK10 and Grey V4 for the SLA and DLP processes. They exhibit a high level of surface roughness, as continuous light scanning and point laser solidification is observed, to embed the pallet surface with alternative cycles of heating and cooling, thus entrapping gas bubbles during the controlled process [17–20]. It is restricted with controlled parameter values, but as indicated in the

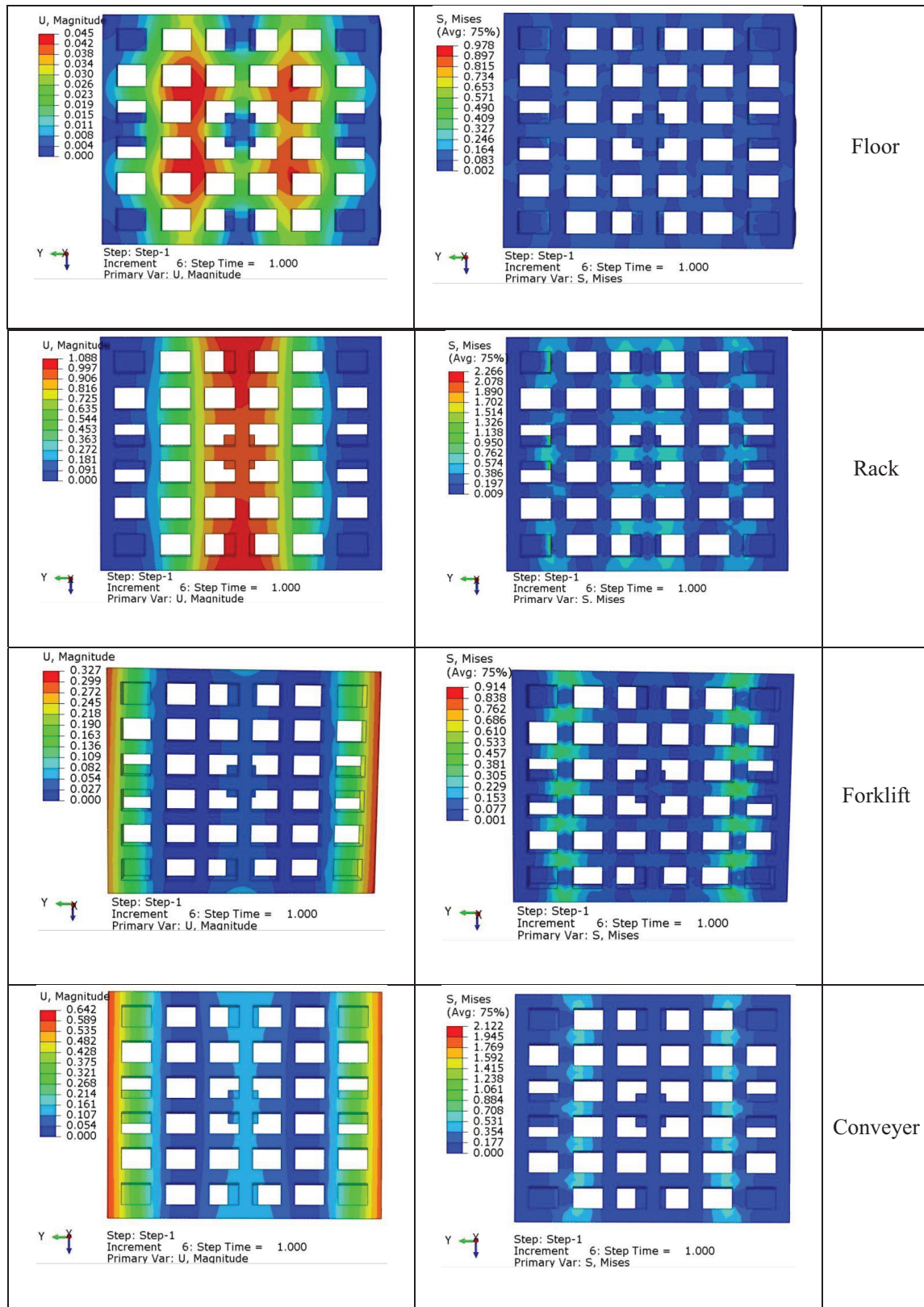


Fig. 29. Displacement and stress contour: optimized pallet design (ABS material)

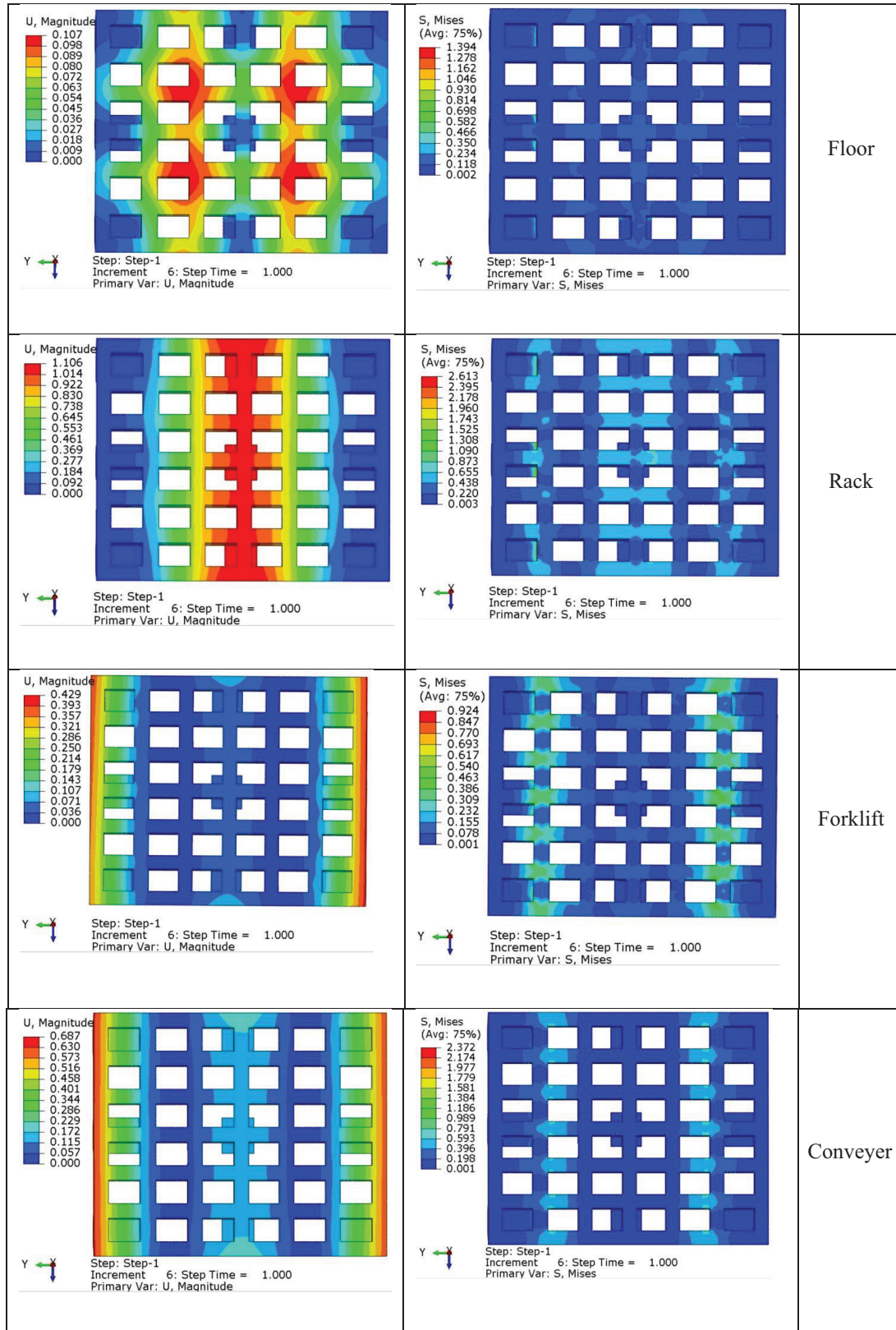


Fig. 30. Displacement and stress contour: optimized pallet design (DLP material)

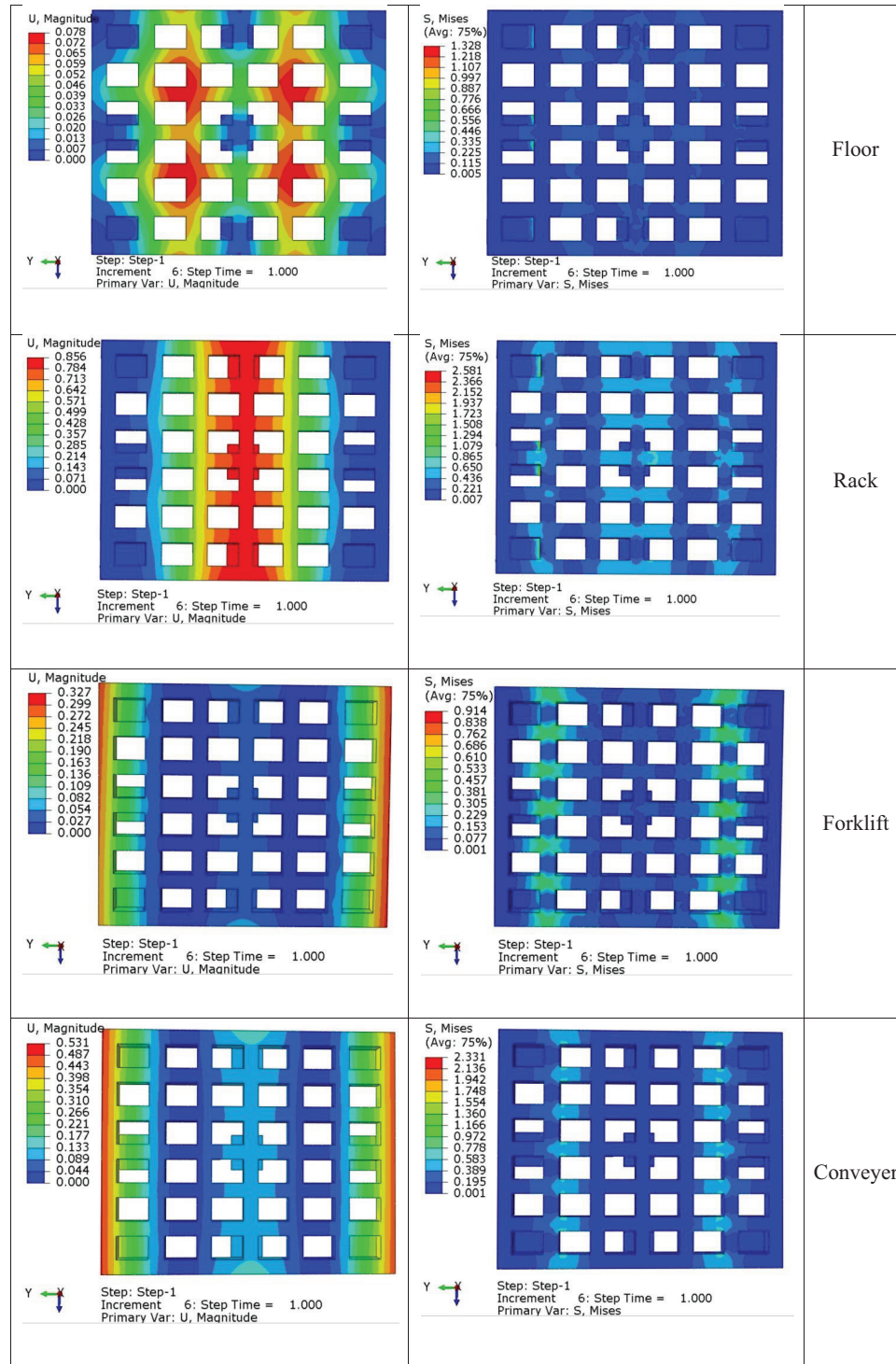


Fig. 31. Displacement and stress contour: optimized pallet design (SLA material)

SEM images in Figure 35, it represents a rough contour with detailed micropores/vacancies inside the surface.

We have observed that a more unilateral distribution of material is ascertained in the DLP process, as the light scanning occurs over a large surface

Table 19. Comparison of rack support vs. floor support, rack support vs. forklift support, and rack support vs. conveyor support for DLP

Comparison for deflection			Comparison for von mises stress		
Rack vs. floor	Rack vs. forklift	Rack vs. conveyor	Rack vs. floor	Rack vs. forklift	Rack vs. conveyor
90.89	61.80	37.97	48.55	64.59	9.69
90.82	61.86	37.88	48.52	64.58	9.72
90.88	61.85	37.87	48.56	64.59	9.76
90.81	61.84	38.01	48.53	64.58	9.76
90.89	61.82	38.00	48.52	64.60	9.81
90.78	61.92	37.88	48.54	64.66	9.81
90.89	61.92	37.85	48.53	64.68	9.89
90.76	61.90	38.10	48.47	64.69	9.92
90.88	61.75	37.89	48.44	64.74	10.06
90.65	61.68	37.85	48.46	64.77	10.31
90.91	62.24	37.76	48.39	64.91	10.78
90.14	61.97	38.03	47.96	65.16	11.76

Table 20. Comparison of rack support vs. floor support, rack support vs. forklift support, and rack support vs. conveyor support for SLA

Comparison for deflection			Comparison for von-misses stress		
Rack vs. floor	Rack vs. forklift	Rack vs. conveyor	Rack vs. floor	Rack vs. forklift	Rack vs. conveyor
90.33	61.21	37.88	46.65	64.64	9.22
90.34	61.24	37.87	46.64	64.63	9.23
90.35	61.28	37.85	46.65	64.65	9.23
90.36	61.33	37.83	46.63	64.64	9.23
90.24	61.25	37.94	46.64	64.60	9.29
90.23	61.24	37.83	46.62	64.59	9.25
90.24	61.30	37.79	46.64	64.60	9.33
90.24	61.17	37.96	46.61	64.59	9.27
90.24	61.25	37.94	46.62	64.60	9.39
90.25	61.37	37.91	46.56	64.58	9.47
90.22	61.41	37.50	46.58	64.61	9.59
90.22	60.87	38.04	46.36	64.55	10.00

in comparison to the SLA surface, as indicated in Figure 35 [29]. With a large area scanning, however, gas bubble entrapment occurs, which reduces strength marginally when the pallet size is slowly scaled up to real-time scale [28] with the SEM image indicating a very rough serrated layer. The pallet surface is characterized by AFM (atomic force microscopy) to understand the nuances of the flow of material during the printing cycle.

The AFM images obtained for DLP- and SLA-printed pallets are showcased in Figure 36, and their roughness values are tabulated in Table 21.

As indicated by the SEM (scanning electron microscopy) image, SLA shows an increase of

Table 21. Roughness values obtained from AFM for DLP and SLA pallets

S. No.	Pallet-making process	Roughness factor (nm)
1.	DLP	95.18
2.	SLA	207.35

54.09% in surface roughness by in comparison to DLP-printed pallets, as seen from AFM analysis [22, 24]. With both of the roughness factors high under DLP and SLA conditions, showing a good factor for stability, such as the friction coefficient factor, will be excellent for holding a product placed on the pallet surface. The material's waviness in the images indicates a great deal of

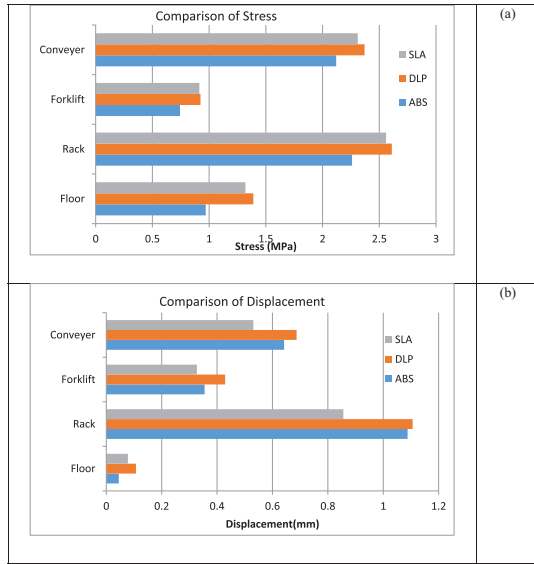


Fig. 32. Optimized pallet analysis correlation to (a) von mises stress (b) deflection

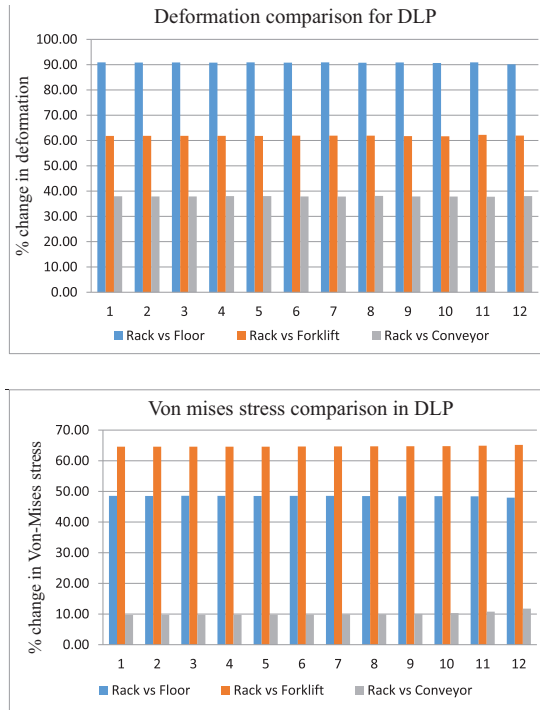


Fig. 33. Deflection and stresses for DLP-manufactured pallet

dispersion along the material's surface, highlighting an increase in the strength of holding material placed on the pallet, as high friction aids in the stability [12, 17, 21].

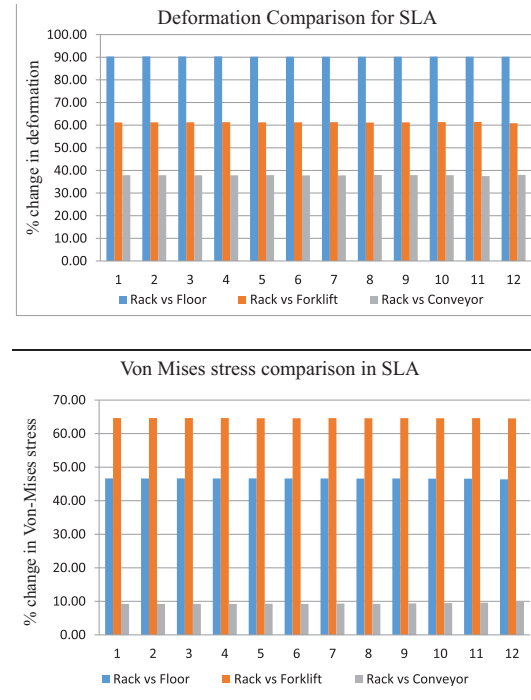


Fig. 34. Deflection and von mises stresses for SLA-manufactured pallet

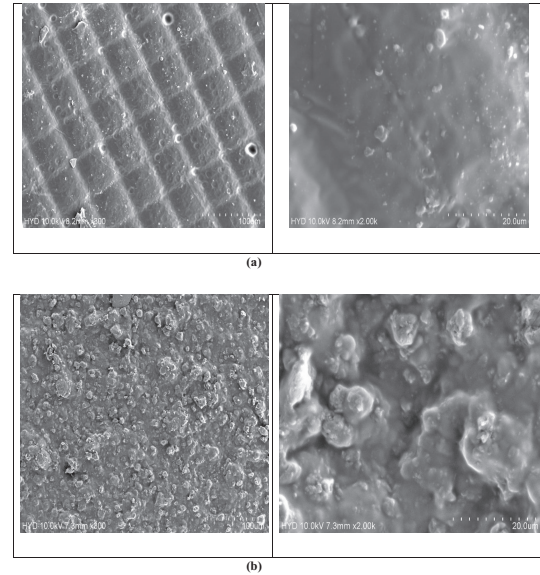


Fig. 35. SEM images for additive-manufactured (a) DLP (b) SLA pallet

Because the material considered is polymer, the peak in XRD is observed at 15° from 19° as depicted in Figure 37, with a wide width, thus indicating a high compressive stress factor.

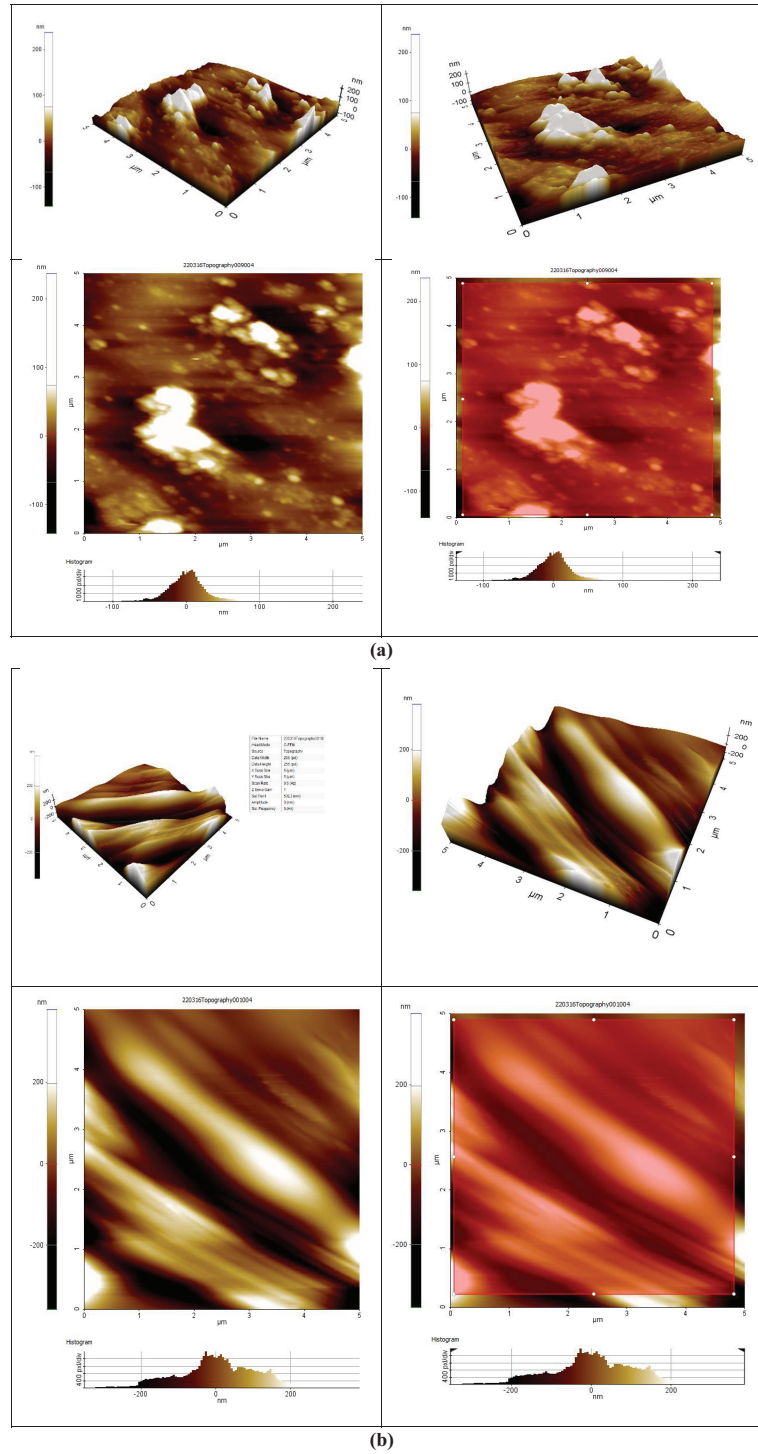


Fig. 36. AFM plots of additive-manufactured (a) DLP (b) SLA pallets

It was ascertained from the information in Figure 37 that under both conditions, the half-width maximum is high, indicating smaller grain size along the surface with curtailed d-spacing amongst

them, thereby forming a passivation barrier which causes a drastic surge in the compressive residual strength modulus in the material. The residual stress values for DLP and SLA are 338.23 MPa and

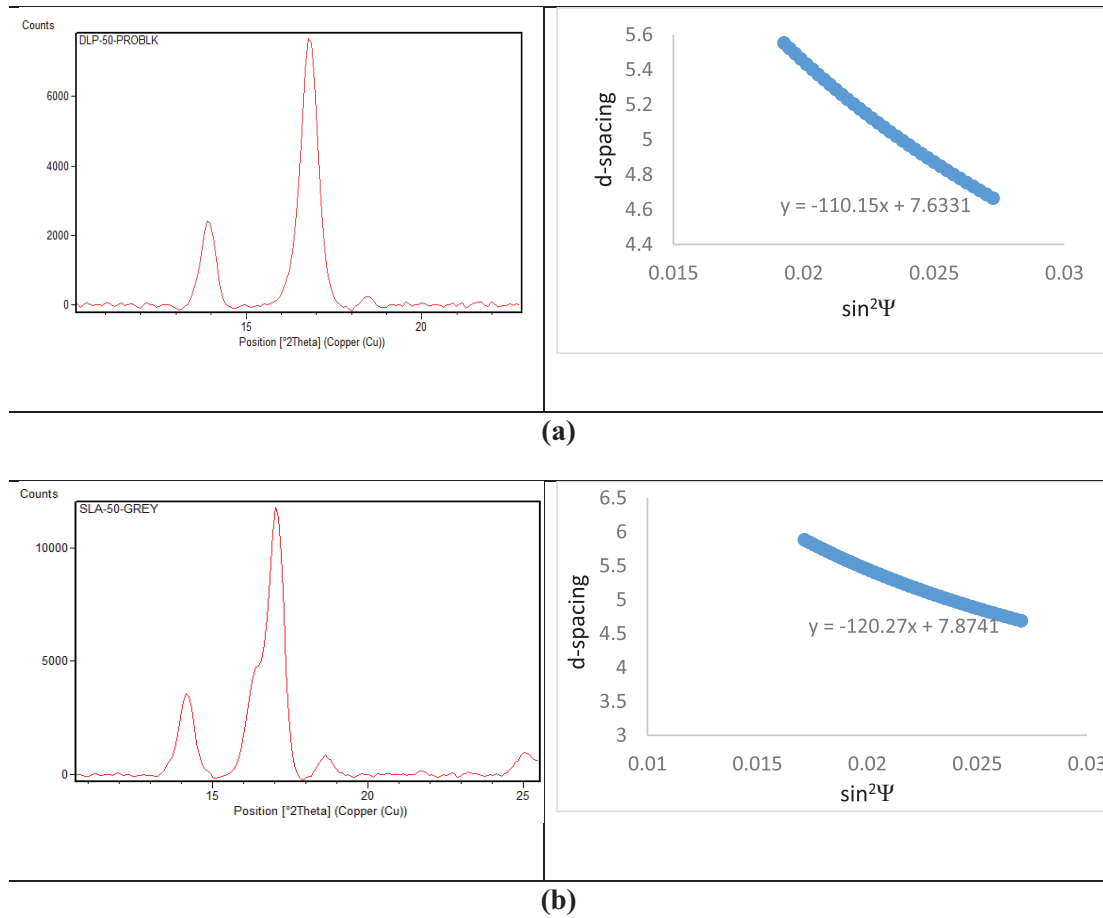


Fig. 37. XRD plots for 3D printed pallets availing (a) DLP (b) SLA

Table 22. Residual stress values obtained from XRD

S. No.	Pallet-making process	Residual stress (MPa)
1	DLP	338.23
2	SLA	122.6

122.6 MPa, respectively, obtained from the $\sin^2\psi$ method, as tabulated in Table 22.

A stark difference of a higher residual stress value of 63.79% is ascertained in the DLP material, owing to its higher flex and tensile modulus. With surface uniform scanning, due to the nature of the DLP process which involves rapid curing of a photocurable resin with light, resulting in nonuniform shrinkage and thermal gradients within the printed part and having an orderly pattern of printing aids in the same as well for colossal residual stress [12, 15]. The pallets formed with a very low d-spacing,

higher residual strength, and polymer nature make them nonreactive to chemicals and external acids and able to withstand high temperatures. The material and the ability to make it on an order basis for small- or large-scale operations make it ideal for replacing old wooden and aluminium pallets, as they ensure sustained, strong, biodegradable and recyclable products.

3. Conclusions

The following conclusions were arrived at after experimental investigation of 3D-printed bio pallets after manufacturing pallet parts using Formlabs Form3 SLA and 3D Systems DLP techniques in comparison to the traditional process.

1. A statistical experiment was adopted to design and print pallets per the MH1-2016 ISO standard, varying their thickness and material 50 correspond to tensile strength, elongation, and hardness.
2. A statistical hybrid method, AHP-TOPSIS, was adopted to find the close-to-ideal solution for the SLA and DLP processes, and the optimum parameters were 50 μm in layer thickness in the SLA and DLP processes, with SLA adopting GreyV4 and DLP ProBLK-10 polymer resins, which was subjected to ASTM D638 type-IV tensile tests.
3. The maximum von mises stresses are 37.78, 43.33, 40.19, 55.76, 57.52, 61.55, 51.31, 54.37, 57.34 MPa for simulation, analytical testing of ABS, GrayV4, and ProBLK-10, respectively. The maximum displacement is 1.80, 1.88, 1.62, 2.89, 2.36, 3.25, 2.88, 2.69, and 3.19 mm for simulation, analytical, and testing of ABS, GrayV4, and ProBLK-10, respectively, showcasing a difference of only 7–12% in correlations to simulated and experimental data.
4. Analytical FEA using a 1D beam element is considered for the pallet one-tenth top deck component of EuroII pallet with five beam elements, for which results compared with 3D-FEA simulations showcased only a 6.5% difference between analytical and simulation results for the displacement factor.
5. Load carrying capacity, with the evaluation of maximum von mises stresses, are analysed for disparate boundary conditions for a UDL of 1000 kg. The maxima and minima of these values ascertained in each stage corresponding to ABS material, the conventional method is 128, 371, 235, and 290 kPa as well as 11, 48, 20, and 25 kPa for the floor, rack, forklift, and conveyor load supports, respectively; for DLP ProBLK-10 material it is 182, 425, 409, and 381 kPa as well as 15, 45, 35, and 33 kPa for the floor, rack, forklift, and conveyor load supports, respectively; for SLA GreyV4 material it is 194, 423, 416, and 383 kPa as well as 16, 38, 36, and 33 kPa for the floor, rack, forklift, and conveyor load supports, respectively.
6. The maximal deflections are analysed for disparate boundary conditions to check the load-carrying capacity for a UDL of 1000 kg. The maxima and minima of these values ascertained in each stage for ABS material are 28, 465, 147, and 163 μm as well as 2, 39, 12, and 14 μm for the floor, rack, forklift, and conveyor load supports, respectively; for DLP material it is 52, 426, 199, and 189 μm as well as 4, 35, 17, 1 and 6 μm for the floor, rack, forklift, and conveyor load supports, respectively; for SLA material it is 71, 430, 271, and 253 μm as well as 6, 36, 23, and 21 μm for the floor, rack, forklift, and conveyor load supports, respectively.
7. The floor support followed by forklift conditions indicates low stress and deformation values in comparison to rack support, which undergoes higher stress and deformation values for ISO MH1-2016 and optimized pallet conditions for materials corresponding to sABS, Grayv4, and Pro BLK-10 in injection moulding, DLP, and SLA process, respectively.
8. From the morphology analysis, higher grade roughness is a found under SLA conditions, with a nonuniform surface. Lower roughness, smooth surface, and intricate structures are observed in DLP, because curing the entire layer of resin occurs immediately, with the unilateral distribution of material, in correlation to the SLA surface.
9. The pallets formed in the SLA process show an increase in surface roughness of 54.09% in comparison to DLP-printed pallets, as obtained from AFM analysis. With both of the roughness factors being high, under DLP and SLA conditions, a good factor for stability is obtained, because the friction coefficient factor will be very large to hold a product placed on the pallet surface.

10. A peak shift is observed in XRD, with an increase of width from 15° to 19° , indicating colossal residual compressive stress of 338.23 MPa and 122.6 MPa for DLP and SLA, respectively. A higher residual stress value of 63.79% is ascertained in the DLP material, owing to its higher flex and tensile modulus.
11. With uniform surface scanning, due to the nature of the DLP process in correlation to SLA possessing lower residual stress, is a result of the factor of rapid curing of a photocurable resin with light, resulting in nonuniform shrinkage and thermal gradients within the printed part and with an orderly pattern of printing.
12. With a very low d-spacing, higher residual strength, and polymer nature, the pallets formed make them nonreactive to chemicals and external acids and able to withstand high temperatures with lower weight ratios. The material and its inherent method to make it on an order basis for small- or large-scale operations make it ideal for replacing age-old wooden and aluminium pallets because they ensure sustained, strong, biodegradable and recyclable products.

Authors Declarations

Ethical Approval

All ethical guidelines of the journal have been followed.

Consent to participate and publication

All the authors declare and give their consent to participation and publication of this research work.

Availability of data and materials

All the data and material used in this study is available from the corresponding author and will be provided to the readers upon request.

Competing interests

The authors all declare no financial or any other competing interests.

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Conflict of Interest

All the authors declare that they have no conflict of interest.

Authors' contributions

All authors share equal contribution in designing, conceptualising, and completion of the manuscript for journal publication.

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