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A Review Based Proposal on the Use of 4D Printing Smart Materials for Automobile Light Cover through Process Structure Performance Linkage with A Sustainable High Throughput Material Development Technique

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ABSTRACT
A lucrative light on the front or tail of a car is the first design feature that catches the potential customer's eye. Despite taking several measures, a cloudy or foggy light cover is quite familiar with the lights' present elements, whether it is a headlight, foglight, rear light, or tail light. This article proposes the high throughput material development of automobile light cover with 4D printing smart materials. After using conventional 3D printing technology such as fused deposition modelling (FDM), stereolithography (SLA), or selective laser sintering (SLS), these self-programmable smart material can change their shape autonomously. Multi-material 4D printing (time as the fourth dimension) utilizes additive manufacturing techniques to fabricate stimulus-responsive ingredients that can actively adjust their properties when subjected to appropriate stimuli like stress, humidity, temperature or solvents, as well as sunlight or pH. This paper illustrates that these 4D printable materials can be a better substitute for traditionally used light cover material polycarbonate, with various mechanical properties like superior transmitivity, opacity, impact resistance with the potential to extend design space beyond integrated geometries. This work discusses the required property combination with Ashby map and delivers some candidate 4D printable multi-material for the automobile light cover. The validation of the material selection is given through Process Structure-Property Combination linkage (PSP linkage) with a high throughput materials development technique of sustainable engineering. Finally, new promenades for the advancement of multi-material 4D printed light covers are proposed, reflecting current paucities and future opportunities for addition by additive manufacturing in the automobile industry.

Keywords: 4D Printing, Smart Material, Shape Memory Effect, Automobile Light Cover, PSP Linkage

1. Introduction

The automobile industry is one of the largest economic sectors by revenue. To maintain continuous improvement, innovation over automobile light cover materials and design is inevitable. Automobile companies take several steps like spraying the protective coating on traditional lightweight polycarbonate light cover to prevent scratches, chips or yellowing from UV (ultraviolet) rays. Despite this, a cloudy light cover with hazes, scratches of a headlight, tail light, rear light or fog light is a common issue that impacts customer satisfaction. The lens of an automobile lamp cover guards the bulb and reflector and concentrates the light where it is most needed. Using 4D Printing smart material with high throughput material development technique as the substitute for polycarbonate for automobile light cover can eradicate all problems related to design, durability, optical properties as well as customer vindication [1,2].

4D (Four dimension) printing smart material opens a new window in the era of additive manufacturing after Tibbits first introduces it in the year 2013 in his speech at the MIT (USA) conference[3]. This specific additive manufacturing technique is a low-cost single step process which has the space for facile and comprisable engineering[4]. Amelioration of the quality of the parts is possible by altering the composition or type of material within layers[5]. 4D printing is the combination of 3D printing materials with the stimuli-responsive smart material[6].

In comparison with 3D printed materials, such stimuli-responsive materials posses an extra dimension (fourth dimension) which is time[7]. When a stimulus like stress, humidity, solvent, UV light, sunlight [5] is subjected to these intelligent materials, they can actively change their shape based on their shape memory effect[8]. Their self-extension and shrinkage capacity makes it possible, which was nearly impossible in the past. Mainly the technology of 4D printing material is similar to traditional 3D printing technology such as vat polymerization, material extrusion or powder bed fusion[6]. After going through with any of this technology's most common method like fused deposition modelling, stereolithography or selective laser sintering, it can change its shape by its self-programmable ability. Precise physical replicates with compact, portable manufacturing are possible where complexity and variety are free with no lead time, less waste byproduct, as well as sustainable customer satisfaction[9]. This revolution has become possible with the collaboration of material science and machine learning as well as its combinatorial approach to high throughput material development technique[4, 5].

The hindrance manufacturer faces in this approach is that manufacturing is complicated, somewhat costly at least at the early stage. They have to deal with toxicity and most importantly, with the limited recovery[5] .Utilizing malleable and robust material is a big challenge due to instability between layers and surface

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finish[4]. That is why for material choice validation and material property validation, this article uses CES Edupack wherewith the required property combination structure and process variables, most valid candidate material list will be proposed for automobile light cover. CES Edupack works based on Ashby map and utilizing the Ashby database [10] where it links up the process, structure, property, performance combination. The system allows the data to be presented that brings out the best interest of features based on Process structure Performance linkage (PSP linkage)[11].
Material's suitably normalized physical responses are known as property. Property depends on the internal structure (like dislocation, defect) which can be on multiple length scales. So the hierarchical approach is to dig deep into structure space. However, the problem is that structure space is quite ample. Looking for this solution, one may look for a hybrid process space. Hybrid process is an ordered sequence of unit manufacturing processes. This hybrid process space can easily relate to structure space and eventually links up with property combination[12]. Nowadays for engineering application with additive manufacturing's design-led top-down approach deals with PSP linkage from the backward direction.[9, 11]

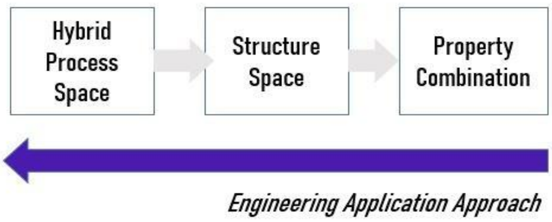

Fig 1: Process Flow diagram for Engineering Approach

In this paper, we propose, with its unique shapeshifting property over a time period, it can optimize the operation cycle of automotive light cover[13]. Effective transformation as shifting the structure to its initial shape can be pre-programmed whenever there is deviation from the ultimate optimum design. This revolutionary work can be possible when there'll use of 4D printing smart material as the light cover material in supercars at the near future by giant companies.

2. Recent advancement in 4D Printing Technology:

Additive manufacturing creates a new era for manufacturing because of its nature of customization, rapid prototyping, fewer assembly steps, material tuning capability, design space beyond limitation, and less waste byproduct[13]. Infinite shapes of materials with designer space is possible with compact, portable manufacturing. In this additive manufacturing genre, 4D printing technology is creating such hypes because of its sustainability, the ability of self-assembly, and digitalization[14]. A wide variety of materials like polymers, metals, ceramics and biomaterials are frequently used in additive manufacturing with the emergence of smart material into the ground. In the recent advancement with the smart materials,[7] it's application is widely found in the automotive sector, aerospace, healthcare, sensors, soft robots, actuators, artificial devices, consumer products and provide an additional dimension of choice so that every product have an ultra-intuitive design to be tailored to a specific customer need[3,6,8]. For the well-controlled manufacturing process, 4D printing is used to the 3D printing of the smart materials that can be transformed its contour based on preprogramming over time in the presence of an external stimulus. It uses programmable matter which produces a product that reacts with parameters within the environment and changes its form accordingly. A 4D print out material or model is basically a 3D print out which later changes its shape based on shape memory effect[1]. 4D printing technology uses unique materials like shape memory alloy, and shape memory polymers are used as raw material to create intelligent dynamic structure. Shape memory polymers are more preferred over shape memory alloy [3] because of their wide glass transition temperature range (-70 °C to 100°C) [5].
The used materials in 4D printing are growing at an extent that there can be biological elements such as BacillusSubtilis which changes their shapes by varying the relative humidity[15]. Softwares built by Autodesk research and nervous systems make it easier to develop in the field of 4D printing[2]. The main section of materials that are used in 4D printing is the shape memory polymers(SMPs). These polymers can restore their dimensions by outside incentive[16].Other materials which can be used as 4D polymers are the hydrogels, and Tertiary shape memory polymers and fiber or nano-particles reinforced polymers[16]–[18]. Introducing time as the 4th dimension materials can recover or reorder in the same way or another[13]. Thus the introduction of the smart materials is arrived at by the concept. Gauthier et al. [19] gave us an idea of how polymethylmethacrylate (PMMA) recovers from elastic scratch with varying strain rates. Vinay Kumar et al. [20] introduced graphene reinforced secondary Acrylonitrile butadiene styrene(ABS) and the validation for the material to be 4D printable. Qiu et al. [21] worked with cellulose-based smart materials and their properties and applications which can significantly work in the field of 4D technology. Mitchel et al. [22] also described several polymers used in technology. Also, there are a large number of polymers besides these which can be used and modified to choose for the correct purpose.
Method of manufacturing is the same as additive manufacturing or 3D printing technology, which has the potential to be an option allowing intricate designs while cutting machinery costs and leaping the assembly details. Although the traditional manufacturing procedures, including forming, casting, molding, and machining, are well-suited for mass reproduction, they suffer from goals on design and restraint complex and multi-material structures[9]. 3D printing has vindicated these restrictions. This bottom-up system is based on the layer-by-layer joining of matters to construct an object from a 3D model. The design thinking of additive

manufacturing genome and value chain integration is crucial with the sense of desirability, viability, feasibility to ideating, prototyping and finally, implementation[12]. Several techniques have been exploited for additive manufacturing of composite material, which can be classified into three main types.

3. Proposed methodology of Using 4D materials in automobile light cover:

3.1 Process Validation:

Table 1: Material Processibility [9]

	FDM	SLS	SL
Polycarbonate	x		
ABS	x		
PC/ABS blend	x		
Polytherimide	x		
PLA	x		
Acrylates			x
Acrylics/PMMA			x
Epoxies			x
Polystyrene		x	
Polyamide		x	
Polypropylene		x	
Polyurethane		x	
Chocolate	x		
Al alloy Ni alloy		x	
Co-Cr alloy		x	
Gold, silver		x	
Ti-6Al-4V		x	
Stainless steel Tool steel		x	

A certain material list is analyzed, which can be used in additive manufacturing genre. From this table, we can indicate that most of the shape memory polymers are best suited for fused deposition modelling (FDM). Self-modified polymers also have the advantages of lightweight, biodegradability, excellent biocompatibility and high flexible impact modifier[3]. Amorphous material like ABS, polycarbonate, PLA can be used because of its gradual softening character and lower residual stress buildup than semi-crystalline thermoplastic. Also going with selective laser sintering and stereolithography is far more expansive and complicated due to the utilization of LASER. Also, SLS is better suited for metal and alloy 3D printing which is very costly, will not satisfy the process's economic goal. On the contrary, FDM is far cheaper when polymers are used in the technique. However, if we think as a whole there are no materials which can be the best one because these materials have many drawbacks in terms of preparing, application, processibility, cost, mechanical behaviors, thermal behaviors, formability and many more. So we must compromise our list of selected procedures if we have to. Thus, this can be the easiest way to introduce 4D printed materials in light cover production.

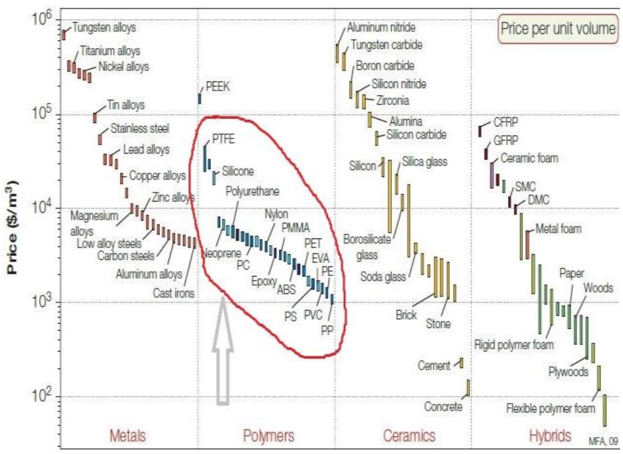

Fig 2: Process validation upon price [10]

From the chart made by CES Edupack, it is vindicated that using polymers, especially self-memory polymer in FDM satisfy our goal, so FDM is the best-suited process among three. However, Gordan et al., [23] found that anisotropic is a big issue for the final product. To lower anisotropic characteristics, thermal conductivity should be increased as high as possible as heat can flow quickly because of efficient bonding. Process linkage of FDM with properties and phenomena is illustrated in Fig 3.

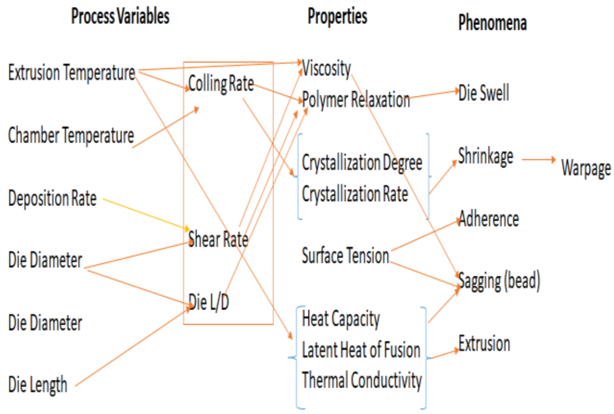

Fig 3: Process variables of FDM with the linkage of property and phenomena[23]

3.2 Material Choice Validation

Objective: CES Edupack is used to select materials that meet the requirements of the automobile light cover with 4D printing smart material. *Requirements:*

• Must be transparent with optical quality with refractive index near to traditional choice of automobile light cover such as Poly Carbonate.

• Must be able to be processed with additive manufacturing's fused deposition modelling.

• Good durability to UV radiation, in water or seawater

• Must have excellent impact resistance to absorb sudden impact with economic flexibility means low cost.

• Good abrasion resistance, meaning a high hardness.

• Must be of low manufacturing cost so that the customers can buy with minimum amount of currency.

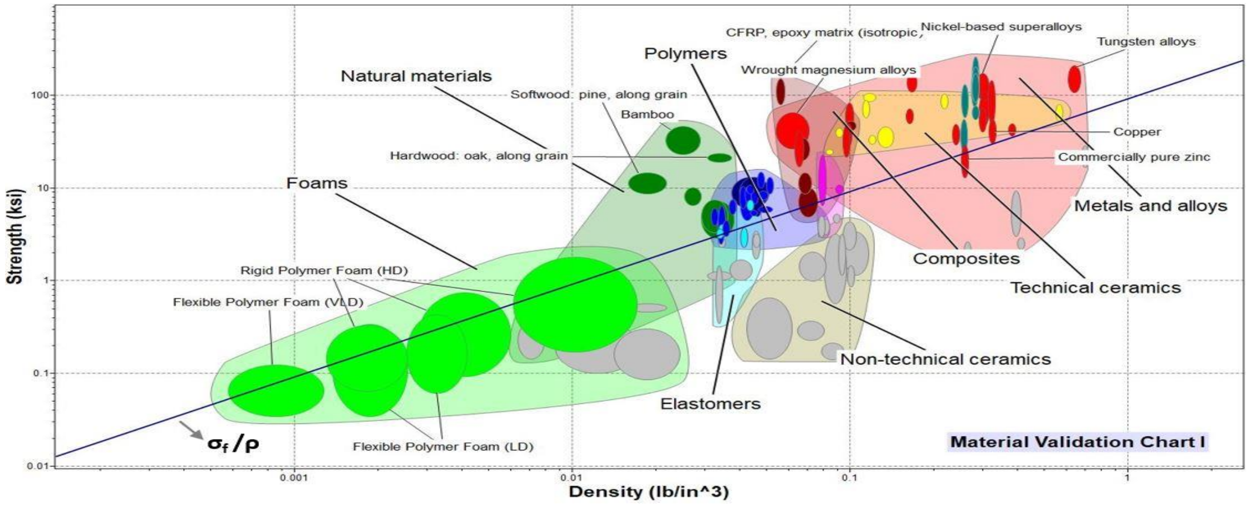

Fig 4: Material Validation Chart I (Strength vs Density)[10]

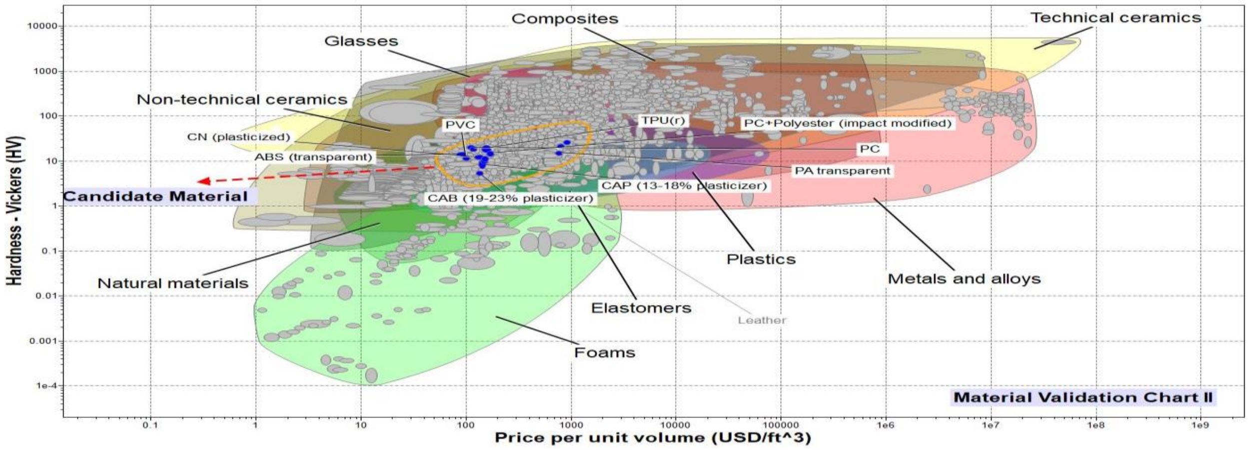

Fig 5: Material Validation Chart II (Hardness vs Cost)[10]

This high throughput material development technique is illustrated at 4 stages.

Stage 1 and stage 2: Property combination with maximizing performance index
Stage 3: Structure space
Stage 4: Process (hybrid process space) collaboration with structure, property and performance

Stage 1: Strength vs Density

For fused deposition modelling and automobile light cover material, property combination between failure strength and density is illustrated in figure 4. So at first, we will define the material's performance index for a light and strong sample with the goal of maximizing performance.

*****Function***: Sample is loaded in compression, compression strength F

****Constraint***: F, Length, failure strength (σ_f)

****Free variable***: cross-sectional area, A.

•***Objective***: reduce mass. m= Al**ρ**

The tie must carry load F without failure: $\sigma_f = F/A$

So, $m=(F/\sigma_f)l\rho$,

Material index, M= σ_f/ρ

Stage 2: Hardness vs Price per unit volume

For the objective of the material's durability and cost, hardness (Vickers) and cost per unit volume (figure 5) relation have bee introduced. From this property combination, a good choice of material can be sorted. Not only property combination, but it also has to be linked with the structure and process to get the final result out of the Ashby map utilizing PSP linkage.

Stage 3: Limiting structure space

After screening with tie line, slope=1 (**σ_f /ρ),** now the candidate material list is sorted. To get the candidate material list for automobile light cover which can be a substitute for traditionally material removal manufactured processed polycarbonate light cover, impact strength (notch) and optical refractive index should be the constraint. In the limiting section, impact strength (notched) at -30 ºC, 4 to 54 ftlbft/in^2 and the optical property is limited to transparent with optical quality. Also, the refractive index is limited to 1.45 to 1.65.

Stage 4: Hybrid Process Space

Finally, from the process universe, additive manufacturing route is chosen for its dimension of design space. Among the various methods of it, the fused deposition method is better suited for manufacturing 4D printing automobile light cover. It is high time that the automobile industry should choose additive manufacturing over other conventional methods like casting, forming, or machining.

Candidate Materials:

ABS (transparent, injection molding)
CAB (12-18% plasticizer)
CAB (19-23% plasticizer)
CAB (4-11% plasticizer)
CAP (13-18% plasticizer)
CAP (7-12% plasticizer)
CN (plasticized)
PA transparent (cycloaliphatic, microcrystalline)
PA transparent (part-cycloaliphatic, amorphous, low Tg)
PA transparent (semi-aromatic type 6I/6T, amorphous)
PC (copolymer, heat resistant)
PC (high viscosity, molding and extrusion)
PC (low viscosity, molding and extrusion)
PC+Polyester transparent amorphous (impact modified)
PVC (rigid, high impact, molding and extrusion)
TPU(r) (molding)

4. Vindication of Candidate Materials:

The following table proves some of the candidate materials have been used for several applications and the outcomes followed by the reference was outstanding regarding the performance of the materials. Based on the recent research on 4D Printing, this table summarizes the vindication of how some of our candidate material can be used as smart material with some modification.

4D Materials	Working Environ-ment	Application	Year	Ref
Graphene reinforced secondary Acrylonitrile butadiene styrene(ABS)	Magnetic Field	Automobile, Electronics	2020	[20]
Cellulose based polymers (CAB/CAP)	pH Light Magnetic field Humidity	Biomedical SMPs Automobile	2013	[21]
Thermoplastc polyurethane elastomer (TPU)	Temperat ure	Robotics, Automobile s	2016	[22]
Coated Polycar bonates(PC)	Temperat ure	Thermo chromic application	2018	[17]
PMMA	Strain	Car Window, Smartphone screens	2001	[19]

PMMA shows scratch recovery behavior over a range of strain applied to the material[19]. Graphene embedded 2nd degree recycled ABS shows magnetic behavior as it gets magnetized as a composite which can be used as smart materials in various fields. The main stimuli here is the magnetic field [20]. With the help of hydrolysis Cellulose nanocomposite reinforced polyurethane has been giving shape memory behavior under stimuli's mentioned in the previous table [21].

5. Discussion:

According to [17] PC still shows quite the same transparency. This could be the magic of 4D technology as non-smart PC can not modify its shape after stimuli. PMMA is scratch recovery material with the property of transmitivity. However, it is not in our candidate list because we limit our choice specifically that is processed through FDM. PMMA is a good choice if one chooses to go with stereolithography rather than FDM. Cellulose-based materials like CAP, CAB are also good candidate material for 4D printing applications in automobile light cover. TPU shows the property of transmitivity only if it is fragile. Graphene reinforced ABS is the right choice for automobile light covers as it will show higher strength and have more scratch resistance properties. So these materials are frequently used in additive manufacturing, and in this article, we have shown the property validation for automobile light cover. All of the candidate's glass transition temperature is within the operational temperature, not very high (80 to 120 ºC). The materials are chosen based on their refractive index which is in between 1.45 to 1.65. Thus, it shows required transmittivity with optical quality which is essential for light cover.

To say the negative aspect, we have to mention that there are some preparational difficulties of Cellulose based nano composites which acts as smart shape memory polymer if used with PU. Also coated polycarbonates have higher cost of preparation and these methods are quite sophisticated. Though There are natural abundance of cellulose based polymer the drawbacks are the preparation and its cost. TPU shows some drawbacks in heat aging and its not very popular to use it as light covers.

So with solving some drawbacks, like volumetric cost and anisotropic behavior this proposed high throughput material development route can make it possible to use 4D printing smart material in automobile light cover.

6. Conclusion:

Material manufacturing genome is rapidly changing over the last decades, and we believe in the next five to ten years, the whole manufacturing process will paradigm shift towards additive manufacturing retrieving an industrial revolution. This article demands to focus on high throughput material development technique in the automobile sector, utilizing structure-property combination. This research work proposes the potential material and vindication based on property and process universe, to use 4D smart shape memory polymers for light cover. Using four-dimensional material in the automobile industry can lessen the waste material, which can undoubtedly create a sustainable circular economy.

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