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Research Progress on the Recycle and Reuse of Wasted Aluminum Substrates of CTP Plates

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Abstract

Recycling and reuse of wasted materials is a key topic in materials research, providing a new material recycling path for green manufacturing. As a national pillar industry, the greening and intelligent upgrading of the printing industry is an inevitable trend in the development of modern printing. To better implement the national "dual-carbon strategy" and cultivate new quality productivity, this paper presents a systematic literature review on the research progress of the recycling and reuse techniques of used aluminum substrates of CTP plates for offset printing. Analysis of existing industry data and literature shows that aluminum substrate of used CTP plates meets the recycle size and required physical and chemical characteristics, but the current research has not yet fully taken into account the integration of technical innovation in the recycling and reuse of aluminum substrate of used CTP plates. Based on material eco-cycling perspectives such as sustainable material utilization design, wasted material recycling device and multi-material fine separation process, this paper provides a unique outlook on the integrated development trend of recycling and reuse of aluminum substrates of used CTP plates, and provides greening case references for the safe management of wasted materials in the modern offset printing industry.

***Keywords:** Aluminum substrate; CTP plate; Property analysis; Material reuse; 3D printing; Waste management*

1 Introduction

Computer to plate (CTP), is a digital pre-press plate production technology with high efficiency and environmental protection, which is to use computers and typesetting software for digital processing of the original text and images by typesetting and editing [1]. Computer direct-to-plate process eliminates the need for film, realizing the direct connection from the computer to the printing, both to save the photopolymer plate (PS plate) with a large number of necessary materials and exposure processing equipment, while reducing the number of image transfer to improve the rate of image reproduction.

CTP plates are plates produced directly using a highly efficient and ecological digitizing technology, which has become a common green plate for modern offset printing companies. According to research data from Verified Market Reports, the global CTP plate market size reached USD 4.17 billion in 2023 and is expected to grow to USD 5.08 billion by 2030 [2]. Data from Zhiyan Consulting shows that China's CTP plate production amounted to 49.98 million square meters in 2021, with imports totaling 3.193 million square meters and exports reaching 16.2236 million square meters, resulting in a domestic demand of 34.0757 million square meters for CTP plates [3]. The China's CTP plate market can be divided into five regions: East China, Central South, North China, Northeast, and Western China. Among these, East China and Central South account for 77.23% of the market share. CTP plate production enterprises in China are mainly located in regions such as Shanghai, Jiangsu, Zhejiang, Sichuan and Henan, with obvious differences among the production processes used in various consuming regions. As the demand and production of CTP plates in China are increasing, the number of discarded CTP plates that have exceeded their service life is also increasing dramatically, which implies that the exploration of safe and efficient recycling and reuse under the green printing strategy has become even more important and urgent.

CTP plates are categorized into four main types according to the imaging principle of plate production: photographic CTP plates, thermal CTP plates, violet laser CTP plates and other CTP plates [4], as shown in Figure 1. The photosensitive CTP plate contains photopolymerized CTP plate and silver salt CTP plate. This CTP plate type system utilizes the photosensitive material on the aluminum substrate, which undergoes a photopolymerization reaction after exposure, and displays the graphic through the photographic process. Photopolymerized CTP plate consists of three parts: a sand-metalized aluminum substrate, a

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photopolymerization layer (composed of film-forming resins, infectious materials, photoinitiators, monomers or zwitterions, stabilizers, and other additives), and a protective layer (polyvinyl alcohol oxygen barrier). The silver-salt CTP plates are mainly divided into silver-salt diffusion transfer plate (mainly composed of plate substrate, silver-salt emulsion layer and physical imaging layer) and composite silver-salt & PS plate (pre-sensitized photopolymer layer, bonding layer and silver halide emulsion layer are coated on the roughened and anodized aluminum plate substrate in turn). With cost advantages of silver salt CTP plate was produced only by Agfa, which was controversial for silver contamination of the waste liquid in the production process of the CTP plate, but only a small portion of the printing enterprises are now in use. Thermal sensitive CTP plates include thermal cross-linking plates, thermal ablative plates and thermal transfer plates. This type of CTP plate triggers a physical or chemical change in the polymer material through heat to form a graphic on the aluminum substrate. Thermal cross-linked CTP plates are mainly composed of a roughened aluminum plate and a single PS photographic layer that receives infrared exposure, while thermal fusion CTP plates are mainly composed of an aluminum plate that does not need to be roughened, an ink-friendly layer and a PVA layer (for conventional offset printing) or a silicone layer (for waterless offset printing). The violet laser CTP plates use the high energy of violet laser in the range of 405 ～ 410 nm to trigger a polymerization reaction of the resin in the photosensitive layer to form a graphic on an aluminum substrate, which is suitable for commercial and newspaper printing with high-resolution requirements [5]. Violet laser CTP plates are mainly composed of an aluminum substrate, a violet light-sensitive layer, and a protective layer of polyvinyl alcohol (PVA), which can be operated under a yellow safety light and have a long lifetime. The composition of these CTP plates reflects the application of different imaging techniques and material science to meet the efficiency, quality and environmental requirements in the offset printing industry. Each type of CTP plate has its own unique advantages and application scenarios, and its substrate is often made of lightweight and strong aluminum sheet.

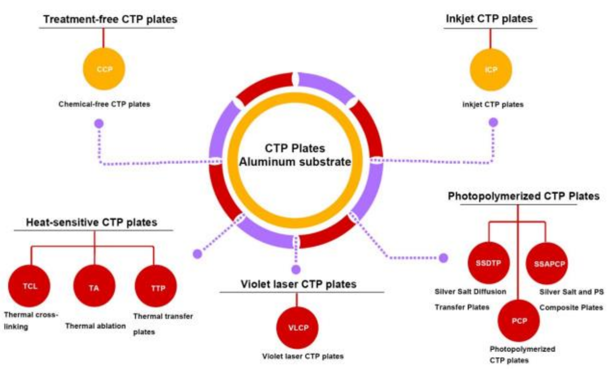

Figure 1 Classification of CTP plates

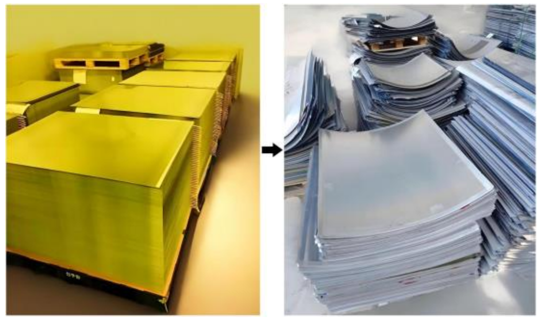

Figure 2 Before and after printing state of aluminum substrate of CTP plates

With the upgrading of the global green printing development, the CTP plate production system continues to innovate with green processes and develops treatment-free CTP plates and inkjet CTP plates. In a broad sense, treatment-free CTP plates can be printed on the printing machine without any subsequent processing after exposure and imaging on the platesetting equipment. Narrowly speaking, treatment-free CTP plates don't need chemical treatment after exposure and imaging on the platesetter, but there will still be individual non-chemical treatment processes. The international suppliers of treatment-free CTP plates include Fujifilm, Kodak, and Agfa, while domestic suppliers include LeKai Huaguang [6]. Inkjet CTP plates are formed by inkjet printing special ink directly on the surface of the aluminum substrate to form a graphic area (oleophilic), while no ink is printed on the part of the non-graphic area (hydrophilic), cured to form a printing plate for on-machine printing [7]. The main suppliers of inkjet CTP plates include well-known companies such as Glunz & Jensen, Zhongke Naxin, and Chengdu Xintu. Since the graphic information on the CTP plate is disposable, the graphic area on the aluminum substrate is cured after printing and can't be removed by conventional methods and restored to its original state for reuse. The current CTP plate production system is almost using aluminum sheet as the substrate, only a very small percentage of the flexible polymer substrate (e.g., polyester substrate) is used. In addition, the natural drying of spent CTP plates mainly contains aluminum substrate and residual curing layers, which can't be directly reused for new plates to be discarded by printing managers in warehouses or pulled to recycling stations, as shown in Figure 2. As a result, there is an urgent need for research on the reuse of spent CTP plates to focus on how to safely and efficiently utilize aluminum substrates by removing the residual curing layers, and to provide a high-value safety management case for the material innovation application for lower cost and higher efficiency of global green printing enterprises.

2 Analysis of Physical and Chemical Properties of Aluminum-based CTP Plates

The main process flow for producing

aluminum-based CTP plates in most enterprises is as follows: the raw material is annealed, cold rolled, straightened, longitudinal cut into aluminum sheet, then conducted the following steps: degreasing, electrolytic sanding, anodizing, photopolymer coating, drying. Among these, the cold rolling and drying procedures directly affect the physical and chemical properties of the aluminum substrate, as well as the number of printings it can endure[8]. Saeed Yaghoubi et al. carried out experimental tests to optimize the shape of aluminum substrate by varying the process temperature and underpressure rate, and analyzed the final thickness distribution and shape accuracy using a digital image correlation system to improve the physical forming accuracy of aluminum substrate [9]. Jia et al. explored the effects of cold rolling deformation and baking on the microstructure, mechanics, and physical and chemical properties of 1060 aluminum alloy for cast-pressed CTP plate, and found that better formability and higher print resistance were achieved with the first pressing rate of 58.2% and the baking treatment of 280 ℃×5 min[10]. On the other hand, Huang approached the target plate shape curve by adjusting the billet plate shape index, and carried out optimization research on rolling and finishing processes, so as to control the final rechecked plate shape of the aluminum substrate of the CTP plate within 6.0I units[11]. In addition, the modern CTP plate production line is basically equipped with automatic defects online detection equipment, such as Japan's FUTEC surface defect detection system for the aluminum coil with a width of 1.9 m and thickness of 0.28 mm when the highest line speed up to 250 m/min. Shen et al. introduced the human visual attention mechanism into the adaptive online detection algorithm of different types of defects on the surface of CTP plates, and reached a resolution of 0.1 mm for rapid detection of multiple types of defects on aluminum-based CTP plates with an average detection accuracy of 96.3%[12]. Meanwhile, in the optimization research of printing resistance of aluminum-based CTP plate, Yang found that the second phase composed of Fe element affects the surface properties of aluminium substrate through the energy spectrum analysis of the original aluminum sample of aluminium substrate, and proposed that controlling the content of Fe and Si and selecting the preferred grain refining methods can effectively improve the printing number of aluminium-based CTP plate. Thus, it can be seen that current research on the physical and chemical properties of aluminum substrates has covered the entire production process of aluminum-based CTP plates and also reflects the dimensional and surface characteristics of each aluminum substrate during both the fabrication and usage stages.

The aluminum substrates of CTP plates exhibit excellent print resistance, high resolution, and strong resistance to temperature and humidity. The commonly used aluminum alloys for CTP plates are 1050, 1060, and 1070, with aluminum content of ≥99.50%, ≥99.60%, and ≥99.70%, respectively. Aluminum coils for CTP plates are usually processed in H18 or H19, which are in a high state of hardness and strength. The thickness of the aluminum substrate of the CTP plate is generally 0.280mm, and some adopt the thickness of 0.275mm. Aluminum substrate has good physical and mechanical properties, manifested in high mechanical stiffness, easy to form, good stability and fine surface treatment. According to the imaging principle of CTP plate and the difference of materials used, the aluminum substrate of CTP plate can also be divided into sand mesh aluminum substrate, roughened and anodized aluminum substrate. Among them, the sanded aluminum substrate has a multi-layered sand structure on the surface, which in turn exhibits good ductility and formability. Commercially available aluminum substrate for CTP plates have a mesh value of Ra of 0.45 to 0.60 μm, with an ideal value of 0.45 to 0.55 μm. The surface of the roughened and anodized aluminum substrate is formed by electrolytic roughening and anodic oxidation of the alumina film layer, which is high in hardness, good in chemical stability, and has high tensile strength and corrosion resistance. For aluminum substrates from discarded CTP plates, the common process involves washing off the ink adhered to the surface, followed by physical stripping of the cured layer and flat pressing, which quickly forms a relatively intact aluminum sheet. In some cases, discarded CTP plates with scratches on the surface due to usage can be coated with a layer of water-based paint to cover or decorate the surface, improving its appearance and making it more suitable for reuse in applications where a good surface finish is required.

In the printing enterprises, especially offset printing enterprises, the workshop needs CTP plate format type and quantity are more, and equipped with CTP plate making system plate format is larger, direct production out of the CTP plate usually need to be cut and punched in order to meet the different printing business requirements. The cutting of wide-format CTP plates can be done either manually with a specific tool or with a simple plate cutting device. This provides precise and easy shaping convenience for the innovative subsequent reuse of spent CTP plate substrates, allowing on-site reuse of spent CTP plate substrates without the need to purchase additional large-scale processing equipment. Acquiring an affordable wire extrusion unit with an FDM-type 3D printer is not a tough choice for a printing company or workshop to achieve a more flexible reuse of the aluminum substrate.

3 Current Situation Analysis of Recycling Technology for Spent Aluminum Sheets Current Status of Recycling and Utilization Technology for Waste Aluminum Sheets

Scrapped metal sheets are becoming increasingly valuable for reuse because of global warming, geopolitical instability and rising raw material costs. Aluminum sheet is widely used due to its light weight, high strength, good densification, and easy cutting, and its applications are mainly in the form of aluminum foil, aluminum sheet, aluminum plate, aluminum cans, and aluminum structures. The recycled volume of wasted aluminum in China continues to be high, growing from 4 million tons in 2015 to 7.8 million tons in 2023. Liu et al. summarized the research progress on primary grade recycling of aluminum cans and demonstrated that recycled aluminum cans have large advantages in terms of energy consumption and carbon emissions [13]. Li et al. summarized the advantages and disadvantages of the existing process methods, such as downgraded recycling, grade-preserving recycling and overgraded recycling of waste aluminum, and thus predicted the most promising technology for recycling waste aluminum [14]. Recycling degree of aluminum sheets varies from actual industrial applications, and its common challenge lies in the effective complexes separation and the precise removal of impurities. Based on the concept of "treating waste with waste", Liu et al. proposed to utilize the aluminum-containing strong alkaline waste liquid after alkali leaching and mechanical separation to compound with polymeric aluminum chloride for the aluminum separated from aluminum-plastic composite packaging waste as well as sewage treatment [15]. International packaging giant Tetra Pak, which is dedicated to the collection and recycling of used beverage paper packaging, has successfully facilitated the development of a 3D printing filament called ALFAPAK 3D between international Ecorevive SRL and material supplier Maip Compounding on aluminum-plastic composites from used beverage paper packaging [16]. Aluminum wire material shows great potential for metal 3D printing applications, pending the development of low-cost new aluminum alloy wire composite forming technology, which will lead to a large-scale solution for high-value reuse of small- and medium-sized aluminum sheets.

Gu et al. successfully separated the cathode material of used lithium-ion batteries from the aluminum foil components using an innovative method combining glycerol heating and mechanical agitation [17], without elaborating on specific aluminum foil reuse ideas. As aluminum sheet material becomes thicker and larger in practical applications, research on its recycling technology needs to move from simple recycling to integrated recycling. Alhefnawi highlights the priority of using recyclable aluminum panels for facade cladding materials in school buildings from a circular economy perspective, even though the thermal comfort of aluminum cladding requires a higher energy budget [18]. From a quantitative analysis of recycling strategies, Zaheer et al. proposed a point-by-point incremental molding process for the reuse of scrapped components with numerical simulation to reduce the geometric deviation, then obtained a robust component with finite deformation [19]. Meanwhile, the reforming recycling route is analyzed in terms of environmental performance with the traditional recycling route and solid recycling route, and demonstrates the advantages of energy saving and emission reduction [20]. Li et al. proposed a laser irradiation followed by mechanical stripping method for recycling the EVA layer on the backside of solar cells in crystalline silicon photovoltaic (PV) modules with respect to the efficient debonding of ethylene-vinyl acetate (EVA) copolymers [21]. Farioli et al. presented a framework for reproduction of curved alloy panels for automotive body panels and optimized the process parameters by using 0.8 mm DC 0.4 alloy panels with specific radii reshaped and flattened under different conditions [22]. For the reuse technology of spent aluminum-based extrusion die, Li Jian empirically proved through practical data that the aluminum profiles produced by using the refurbished and modified spent die can meet the requirements of construction use [23]. According to the production statistics of aluminum plates and strips from China Nonferrous Metals Processing Industry Association, the output of aluminum plates and strips in China in 2021 were 13.35 million tons, of which 500,000 tons of printing plate substrates were produced. This indicates that the recycling scale of aluminum-based plates is considerable, but the recycling ratio of aluminum -based CTP plates is yet to be improved.

4 Prospects for Integrated Recycling and Reuse Technology for Aluminum Substrates of Spent CTP Plates

The integrated technology of recycling and reuse of aluminum substrate for spent CTP plates refers to a series of processes to separate, recycle and reprocess aluminum substrate and other materials (curing layers) from spent CTP plates into new functional materials. This improves the recycling efficiency of spent CTP plates, reduces costs and environmental impacts via a top-level design perspective, achieves the resourceful utilization of the recycled aluminum substrate, and promotes the transformation of the printing industry into a green circular economy. The key to its realization lies in sustainable material utilization design enhancement, spent material recycling device optimization and multi-material fine separation process advancement.

4.1 Sustainable material utilization design enhancement

Sustainable material utilization design is mainly embodied in sustainable product integration design and closed-loop recycling system design, the former requires a full understanding of the physical and chemical properties of materials based on innovative structure or functional product design, and the latter focuses on the construction of the material recycling system under the reuse of the ecological carbon footprint planning. Current research status of sustainable product integration design of aluminum substrate shows that this field is gradually becoming a hotspot in the intersection of industrial design and material science. From the industrial design perspective, the surface microstructure design and three-dimensional modeling of aluminum substrates of spent CTP plates offer infinite possibilities for sustainable material utilization. The main processing requirements are concentrated on mechanical strength and surface properties needed for physical operations like cutting, engraving, or folding. For example, after the surface curing layers of aluminum substrate of CTP plates scrapped in the printing workshop are removed by mechanical grinding, the creases and cutting paths required for the forming of common items in the workshop can be creatively generated by using AI technology to further develop innovative applications such as the re-foldable mosquito coils holders, polygonal convenience trash cans and optical disk holders, as demonstrated in Figure 3.

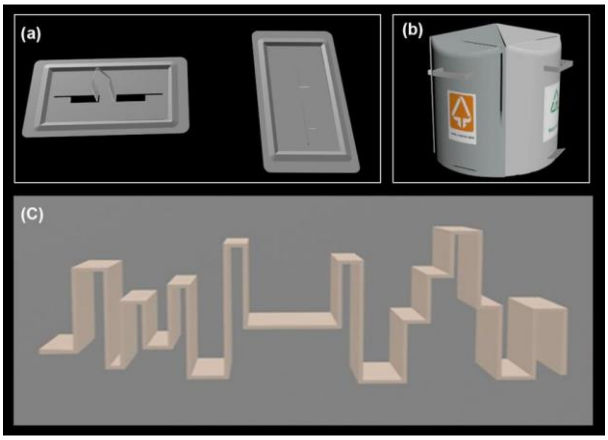

Figure 3 AI-generated creative cases for reuse of aluminum substrates: (a) Mosquito coil holders; (b) Trash cans; (c) Optical disk holders

The research focus of the closed-loop recycling system design is on how to efficiently build a complete circular chain from production to consumption to recycling, aiming to achieve efficient reuse of resources and minimize environmental impact through technological innovation, process optimization and policy support. In other words, it ensures that materials can be recycled and reprocessed many times throughout its entire life cycle, thus reducing resource consumption and waste generation, as well as promoting the low-carbon development of the functional use of spent materials. For example, Fujifilm has launched a closed-loop CTP plate recycling network to greatly reduce environmental loads and CO_2 emissions in the integrated recycling process of aluminum substrate of CTP plates, in cooperation with printing companies, newspaper publishers, aluminum recycling companies, alloy manufacturers, and roll manufacturing plants [24]. Thus, researchers can further explore how to minimize the environmental impact of aluminum substrates of CTP plates at all stages of design, fabrication, usage, and recycle and reuse.

4.2 Spent material recycling device optimization

In terms of the circulation environment, once the recycling path of spent materials has been determined, the recycling department adopts the spent material recycling device for processing and preparing the required physical and chemical properties for the next reuse step. Innovations in digital technology have led to more efficient recycling units, such as the thermal CTP plate recycling device, which improves the efficiency of the physical recycling of aluminum substrates by automating the guiding, leveling, auxiliary folding and flattening mechanisms [25]. Currently, innovative development of wasted material recycling facilities focuses on individual devices or complete production lines for catalytic cracking, catalytic hydrocracking, hydrocracking and component purification. BASF in Schwarzheide, Germany, established the first adjacent battery metal materials production and recycling center in Europe, including high-performance cathode active material production and battery recycling equipment [26]. This center is able to collect waste batteries and recover metal raw materials for the production of new battery materials, realizing the closed-loop recycling of battery metal materials. In recent years, the innovative research of recycling devices for aluminum-based waste materials have all relevant authorized invention patents, including aluminum chips recycling device, aluminum dregs recycling device, aluminum ash recycling device, aluminum foil recycling device and so on. In addition, the utilization of AI technology in wasted material recycling management greatly improves the fine separation of multiple materials between multi-process units. For example, AI vision-based rapid inspection devices can identify and reject real-time defects in recycled aluminum substrates [27], AI-controlled industrial robots can accurately classify and finely dismantle complex aluminum substrate products [28], and AI algorithm-based aluminum composition decontamination devices provide intelligent generation of refined and decontaminated material recipes [29].

4.3 Multi-material fine separation process advancement

The cured layers of graphic info on aluminum-based CTP plates are tightly bonded to the surface of the aluminum substrate, which makes the stripping process complex and difficult to remove completely. Judging from the material composition, the curing layers attached to the aluminum substrate of CTP plates are mainly the curing layers of photopolymer and residual ink co-mingled on the multi-layer sand mesh of the alumina, which are connected very densely. Traditional stripping methods are not yet able to effectively remove the curing layers, while may cause scratches, deformation and other damages to the surface of aluminum substrate, affecting its closed-loop recycling value. In the grade preserving recycling process of aluminum substrate, the existing chemical stripping agents mainly include strong acid stripping agent, dry ink removal cleaning agent, pure solvent-based stripping agent, and eco-friendly stripping agent, among which the principle of efficient stripping of eco-friendly stripping agent, which is the most popular, needs to be further investigated. The development of stripping process with ultrasonic co-frequency technology [30] assisting eco-friendly organic surfactants will be the best green option, which is expected to break through the advanced waste-free process. However, in the degraded recycling process of aluminum substrate of CTP plates, many other non-aluminum components are mainly removed directly by physical stripping process, which in turn focuses on the reuse innovation of recycled aluminum. This method can reduce the reuse cost of recycled aluminum, although the amount of recycled aluminum is reduced to a certain extent, requiring a greater increase in novel high-value applications of recycled aluminum. For example, finely 3D printing aluminum powder for electron beam melt forming can be further 3D printed into high value-added personalized engineering components such as aluminum-based energy-containing components [31], automotive porous aluminum alloy cushion bumpers [32], and high-performance reflective aluminum mirrors [33]. If the expansion of the upgraded recycling process of aluminum substrate of CTP plates, the most urgent innovation lies in the fine control process of the chemical composition on the surface and internal of the aluminum substrate, which is not yet a mature industrialized application. As a result, solving the key materials, core devices and control software restricting the source reduction and harm reduction of waste materials will improve the green and intelligent level of the integrated equipment for recycling and utilization of aluminum substrate of CTP plates.

5 Conclusion

As a green plate material common to modern offset printing enterprises, the number of aluminum substrates of CTP plates for production needs and printing scraps in China is growing rapidly, which is inseparable from the research on the integrated technology and equipment for recycling and utilization in a safer, higher and green way. Starting from the management practice of spent aluminum substrates, this paper elaborates the plate production process, physical and chemical properties and recycling features of spent aluminum substrates of CTP plates, and further outlooks on the development challenges of the integrated recycling and reuse technology. It is worth noting that the high-value use of recycled scrap aluminum substrate requires further application of artificial intelligence technology and 3D printing technology, and the integrated new processes and materials required for the transformation of green printing under the national "Double Carbon" strategy have become more significant. Thus, this urgently requires a sufficient understanding of the green recycling path of multiple materials in parallel in the green printing flow, and further optimization of the refining and purification process of waste aluminum material, which is expected to break through the high-value reuse technology of the entire component of the aluminum substrate.

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