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Improving Thermal Performance and Longevity of Tower Solar Power Plant Receivers Using Coating

Florica Cosmina Carmen
Politehnica University of Timisoara, Romania
cosmina.florica@upt.ro

Florea Mihai
ISIM, Romania
mflorea@isim.ro

Abstract

The paper focuses on the use of coating technology as an advanced solution to improve the thermal efficiency and durability of solar receivers in tower solar power plants. These power plants use concentrated solar radiation to produce electricity, with the solar receiver serving as a critical component in absorbing and converting solar energy into heat. High temperatures and thermal cycling lead to material degradation, reducing efficiency and lifespan. Coatings offer superior thermal resistance, corrosion protection, and enhanced mechanical properties, making them a promising alternative to conventional receiver materials. By improving heat absorption and reducing thermal stress, these coatings contribute to increased operational efficiency and extended service life of solar receivers. This paper examines the benefits of coatings through experimental analysis, discussing their impact on performance, sustainability, and economic viability in the solar power industry. The findings highlight the potential of coatings to optimize renewable energy generation.

Keywords: coatings, solar power towers, solar receivers, metal oxide multilayer coatings.

INTRODUCTION

Coating technology can be beneficial for tower solar power plants (Mohanad Salih Mahdi, 2021). Solar tower power plants utilize concentrated solar power (CSP) systems, with the receiver being a critical component subjected to extreme conditions (Burke, 2018). Central receiver systems with open volumetric air receivers have shown high robustness and efficiency, with recent developments focusing on increasing thermal receiver efficiency above 85% (Wang, 2021). The design of the solar tower receiver plays a crucial role in determining the plant's efficiency, with novel concepts like receiver tubes with helical fins showing significant improvements in heat exchange and thermal conduction (Qiu, 2018). Dynamic and comprehensive models for solar tower receivers have been developed to address

operational challenges and optimize temperature control strategies, contributing to the formulation of effective control strategies for solar power tower stations (Hoffschmidt, 2012).
The study explores the application of coating on solar receivers and investigates its impact on thermal performance and durability. The article discusses the microstructure, surface characteristics, and thermal properties of coated solar receivers using techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and thermal conductivity measurements.

Materials and Applications

Coatings find use across a wide array of engineering and manufacturing applications to improve the surface properties of components. This enables the creation of cost-effective, high-performance parts from inexpensive or lightweight materials with a functional surface (Astolfi, 2017). Commonly coating materials include:

- Cermets (e.g. WC/Co, WC/Co/Cr, Cr3C 2/NiCr, NiCrSiBC);
- Ceramics (e.g. Cr2O3, Al2O3, ZrO2);
- Metal alloys (e.g. steels, nickel, chromium and cobalt alloys including NiCrSiB and MCrAlYs);
- Pure metals (e.g. Ni, Cu, Al, Mo, Ti);
- Polymers (e.g. polyester, nylon);
- Composites (e.g. Ni-graphite).
- HVOF spraying can produce coatings for:
- Wear protection;
- Low friction surfaces;
- Corrosion protection;
- High temperature oxidation resistance;
- Electrical insulation;
- Repair and restoration of damaged components.

Impacts of coating on the mechanical and tribological characteristics of materials

Chromium is known for its superior wear and corrosion properties, along with good lubrication and chemical resistance, making it widely used for both decorative and practical applications. However, the need to identify alternatives or improve the mechanical properties of chromium electroplating is very important, primarily to mitigate environmental pollution and enhance the fatigue strength of the substrate. Chromium coatings are primarily used to enhance the wear and corrosion properties of the component. However, a significant byproduct of this process is hexavalent chromium (Cr^{6+}), which poses a threat to the environment.

SOLAR POWER TOWERS AND SOLAR RECEIVERS

Solar Power Towers

A solar power tower, also known as a **central tower** power plant, is a type of solar furnace that uses a tower to receive focused sunlight. This system utilizes a series of flat, adjustable mirrors, known as **heliostats**, to concentrate the sun’s rays on a collector tower, which serves as the target. Concentrating Solar Power (CSP) systems, like solar power towers, offer renewable, pollution-free energy.
Early designs used focused rays to heat water and generate steam to power turbines. Newer designs use liquid sodium or molten salts as working fluids. These working fluids store energy, allowing continuous

power generation even after sunset or during cloudy periods. Solar power towers are cost-effective and can reach temperatures of up to 500°C, driving turbines coupled to generators.

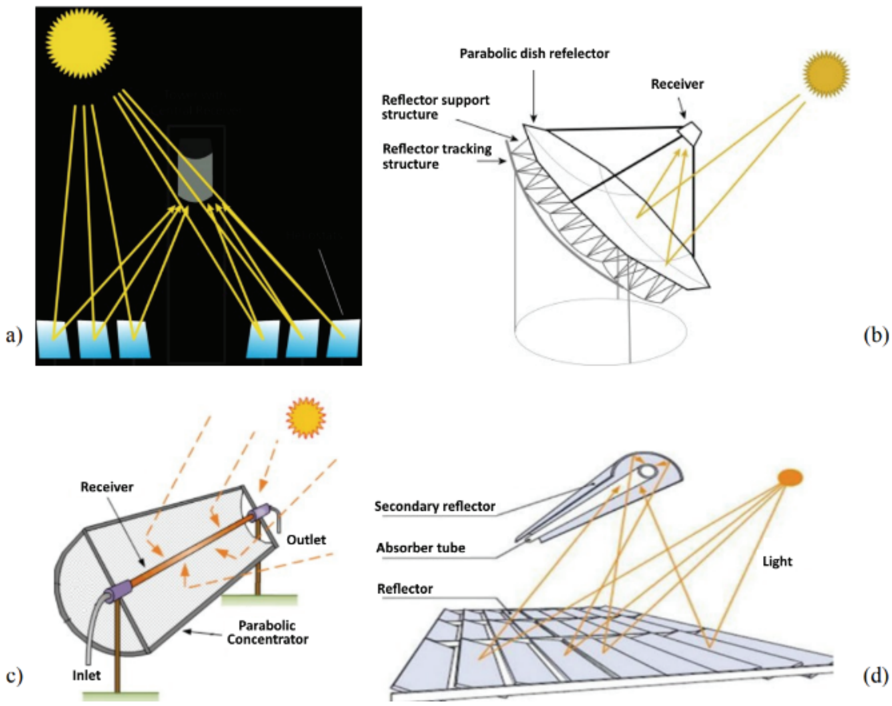
Solar Receivers

Solar thermal receivers play a crucial role in solar power tower systems. They convert solar radiation into heat energy, which is then transferred to a working fluid (usually air or liquid). Various types of solar receivers exist, including flat-plate receivers, compound parabolic receivers, evacuated tubes, parabolic troughs, parabolic dishes, Fresnel lenses, and field collectors. The choice of receiver depends on the specific solar power tower design and application.

Solar energy, when harnessed effectively, can address energy crises, and contribute to sustainable power generation.

Oil, coal, and natural gas are non-renewable energy resources that produce environmental problems. Due to the above major reason, renewable energy resources have been attracted by science attention, especially solar energy utilization technology. For the power generation purpose, concentrating solar power) CSP (is considered as one of the most useful technologies when a thermal energy storage system combined with it. To date, four fundamental designs of concentrating solar power technologies have been implemented. These include the central receiver tower or solar power tower (SPT), the parabolic trough collector system, the parabolic dish collector system, and the linear Fresnel reflector system, as depicted in Fig. 3.

Picture 3: CSP concepts: (a) Central receiver tower (Astolfi, 2017), (b) Parabolic dish collector (Blanco, 2017), (c) Parabolic trough collector (Ghasemi, 2016) and (d) Linear Fresnel reflector

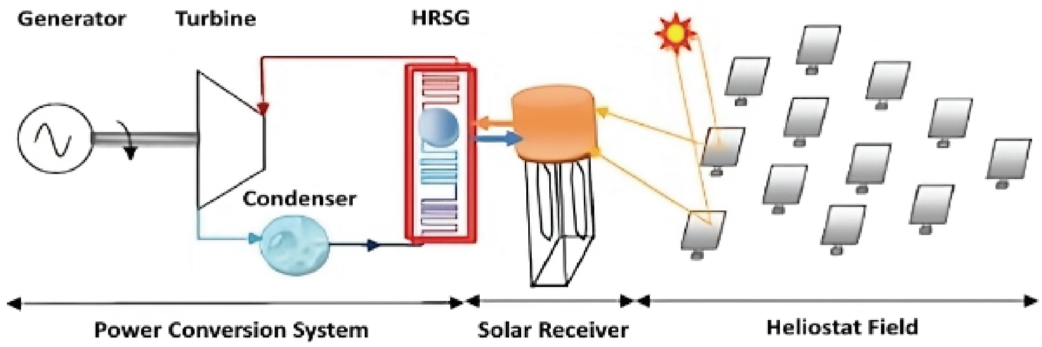


Adapted from HVOF Coating.

For bases that require large-scale energy utilization, the Central Receiver Tower System (CRT) is seen as a promising technology (Luo, 2015; Kim, 2015). This is due to the system's impressive performance with an extremely high solar concentration ratio, as depicted in Fig. 4, in addition to the reduction in

energy costs (Srilakshmi, 2015). A CRT plant features a solar receiver positioned above the tower, with hundreds or more heliostats surrounding the tower to reflect solar radiation and heat the receiver's heat transfer fluid. This system, equipped with a highly concentrated solar field and an updated solar receiver design, can generate higher temperatures than other systems (Lovegrove, 2012). These systems are utilized in a different thermodynamic cycle as a power conversion system. The solar receiver is the most vital component of the solar power tower. Up to now, four types of receivers have been explored: tubular external receiver, tubular cavity receiver, volumetric receiver, and particle-based receiver. Upon comparing these typical receivers, the external receiver emerges as the promising choice due to the large-scale solar energy utilization facilitated by the surrounding heliostat field (Behar, 2013).
The functioning of a solar central receiver tower plant. The central receiver tower systems are made up of three primary elements: the solar field, the solar receiver, and the power conversion system, as illustrated in Fig. 5.

Picture 5: The key elements of the solar central receiver tower plant



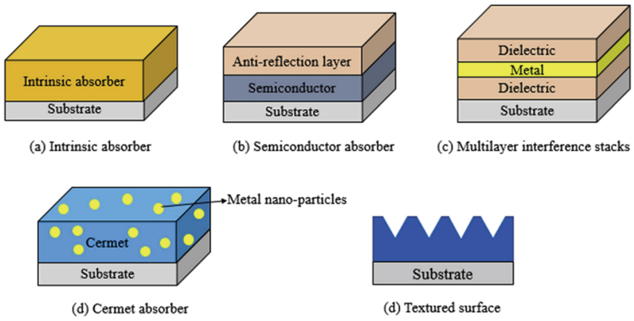
Adapted from Behar (2013)

The solar field is made up of numerous mirrors, known as heliostats, that track the sun. These mirrors reflect the sun's rays onto the surface of a solar receiver located atop a central tower. The solar receiver, functioning as a heat exchanger, absorbs the solar radiation, thereby heating the heat transfer fluid within it. This fluid can reach extremely high temperatures, exceeding 500ºC, especially when using a molten salt (Wang, 2020; Wang, 2017) heat transfer fluid or any other suitable fluids (Blanco, 2017). This heated fluid can produce superheated steam, which can be used to generate electricity in traditional steam power cycle plants or other power conversion cycles.

A REVIEW OF HIGH-TEMPERATURE SELECTIVE ABSORBING COATINGS FOR SOLAR THERMAL APPLICATIONS

Since introduction of the idea of Spectrally Selective Absorber Coating (SSAC), there has been significant interest in the creation and design of these coatings. Achieving maximum absorption with a single layer is challenging. However, by altering the structure of the coatings, selecting different materials, or changing the deposition method, it's generally possible to optimize spectral selectivity. Based on their absorption mechanisms and design principles, these SSACs can be divided into five distinct categories, as shown in Fig. 6., including: a) Intrinsic absorber, b) Semiconductor absorber, c) Multilayer interference stacks, d) Cermet absorber, e) Textured surface.

Picture 6: Representation of five common solar absorber coatings



In recent years, the focus of research has been on the Long-Term Thermal Stability (LTTS) of solar selective coatings in both vacuum and air environments. Given their superior thermal stability and reduced thermal emittance, numerous efforts have been made to develop high-temperature solar selective coatings. This process often involves optimizing the absorption layer. Based on the absorbing dielectrics, these coatings are mainly categorized into three types: double cermet solar selective coatings, transition metal nitride multilayer coatings, and transition metal oxide multilayer coatings. In this section, we present examples of typical coatings, explore the primary failure mechanisms, and identify promising systems that can achieve high conversion efficiencies above 400°C.

Double cermet solar selective coatings

In the realm of large-scale Concentrated Solar Power (CSP) fabrication, double cermet solar selective coatings are a leading area of focus due to their superior optical performance and thermal stability. Siemens, a German company, has commercialized W-Al2O3 and Mo-Al2O3 coatings, which exhibit thermal stability in the range of 350-500°C. Additionally, Mo-SiO2 and AlN-based ceramics have been brought to market by Angelantoni ENEA in Italy and Turbosun in China. However, these coatings tend to have a thermal emissivity of more than 10% at high temperatures, particularly after prolonged annealing.

Advancements in cermet layer development have enabled some coatings to achieve thermal stability up to 600°C. This is achieved by controlling the diffusion of metallic elements and enhancing the heat resistance of dielectrics. Various cermet coatings have utilized Al2O3, AlN, SiO2, YSZ, and AlSiOx as a matrix for high-temperature stability, in conjunction with metal particles such as Ag, Mo, W, Ni. For example, Al2O3 is recognized as a dielectric material in cermet-based coatings due to its low refraction index (n = 1.65) and high thermal stability.

High-temperature transition metal nitride multilayer coatings

Dielectrics in cermet solar selective coatings are predominantly fabricated by radio frequency sputtering of oxide ceramic targets. This process, while slow, facilitates the formation of the dielectric insulating film. However, the metal particles in the cermet are prone to oxidation, which can lead to a decline in spectral selectivity. To address these challenges, there was a suggestion to use double metal nitride coatings that include M-AlN, such as Al/W-AlN/AlN, Al/Mo-AlN/AlN, and Al/SSAlN/AlN coatings. Transition metal carbides and nitrides, like HfC, TiC, TiN, ZrN, etc., also known as ultra-high-temperature ceramics, are increasingly being considered for use in solar receivers due to their inherent spectral selectivity. Among these, TiC stands out because of its hardness, making it a popular choice for reinforcement in ceramic particles, and its inherent spectral selectivity.

Many efforts have been made for the metal of group III A, IV B, V B, VI B and their nitride/carbide/oxide based on coatings due to their chemical inertness, thermal stability, spectral selectivity, and good oxidation resistances. Absorbing coatings can be primarily categorized into three types based on their basic composition: XAlN/XAlON, X(Y)SiN/X(Y)SiON, and XY(O)N. Here, X and Y represent transition metals from groups III A, IV B, V B, and VI B.

XAlN/XAlON Absorbing Coatings: XN is known to exhibit metallic properties, while AlN shows covalent characteristics, and Al_2O_3 displays ionic traits. AlN has a wide band gap (6.2eV), a refractive index of 1.9 to 2.1, a high decomposition temperature (2490°C), and excellent chemical stability (up to 700°C in air). The inclusion of Al and O in the nitride matrix in XAlN and XAlON layers alters the "d" orbital electron density of transition metals, leading to changes in the bonding structure. These changes not only result in the formation of potential compounds but also modify the electrical and optical properties of the layers. This is expected to lead to high absorptance in the solar spectrum and low emittance in the IR range. XAlN/XAlON coatings based on different elements are being explored for their spectral selectivity and aging mechanism (Astolfi, 2017).

X(Y)SiN/X(Y)SiON Absorbing Coatings: Due to their low vapor pressure and refractory characteristics, metal silicide's exhibit stability at elevated temperatures. Concurrently, silicon nitride can function as an insulator matrix in metal/ceramic granular systems, thanks to its optical transparency, transport properties, and resistance to chemical reactions at high temperatures. It has been reported that silicon may exist as an amorphous phase of either silicon nitride or free silicon for X(Y)SiN, where X and Y represent Al, Nb, Ti, Cr, Zr. Owing to their refractory characteristics and low vapor pressure, solar selective absorbing coatings that contain Si appear to withstand higher temperatures than XAlN/XAlON after being annealed for more than 100 hours.

Recently, there have been interesting attempts to use transition metal carbides and carbonitrides by adjusting their compositions and thicknesses during sputtering for photothermal conversion applications. There was developed a novel nanostructure tandem absorber, where TiAlSiCO and TiAlSiO function as semi-transparent and anti-reflecting layers, respectively. The tandem absorber was stable up to 325°C in air for 400h and up to 650°C in a vacuum for 100h, making it suitable for high-temperature solar thermal power generation applications.

XY(O)N Absorbing Coatings: Single transition metal nitrides, including TiN, CrN, ZrN, and others, do not demonstrate adequate solar absorptance and minimal thermal emittance. Therefore, extensive research efforts have been made on binary transition metal nitride/nitro-oxide coatings due to their efficient performance as diffusion barriers and high-temperature oxidation resistance. Choosing reliable materials with excellent mechanical properties and thermal stability is decisive for XY(O)N absorbing coatings. It has been reported that TiN, ZrN, and TiZrN have high thermal and chemical stability, high hardness, and low electrical resistance.

Thermal cycling tests showed that the absorber exhibited excellent thermal stability in a vacuum at 650°C for 100h. However, the selectivity (6.72) still needs further optimization.

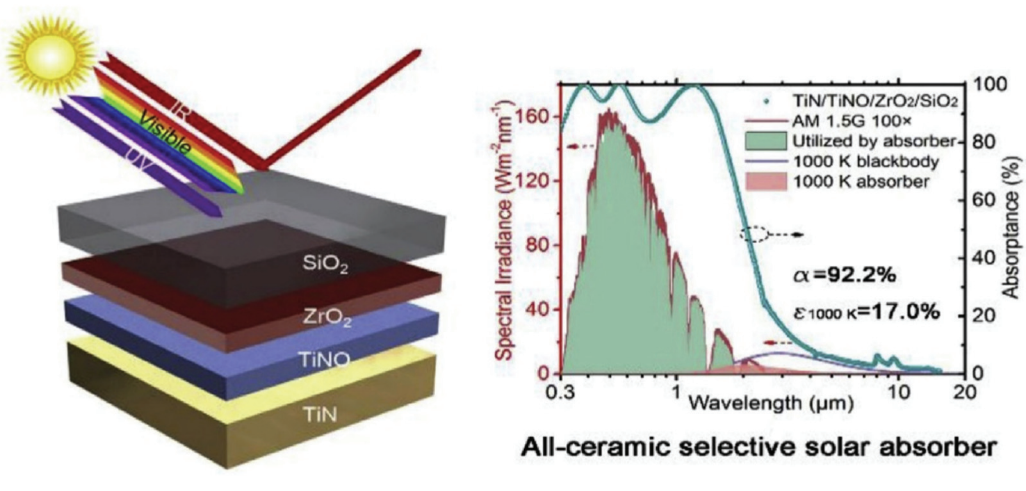
Multilayer coatings of transition metal oxide for high-temperature applications

Double metal/ceramic solar selective coatings are notable for their exceptional spectral selectivity, and have achieved widespread commercial success for applications below 400°C. However, the thermal stability of commercial cermet, typically less than 600°C, does not meet the needs of next generation Concentrated Solar Power systems (CSPs). To enhance the air stability of absorbing coatings, several transition metal oxide multilayer coatings have been developed. A four-layer CrN/Cr-OD/Cr-OM/SiO_2 coating was fabricated using the DC reactive magnetron sputtering technique. The spectral selectivity remained at 0.930/0.073 (at 80°C) after being aged at 278°C in air for 300 hours, but it significantly deteriorated after 600 hours. This degradation was primarily due to element diffusion and chemical interactions near the interface. Black-coloured transition metal oxides (Fe, Cu, Cr, Mo, and Co) with a spinel structure are also promising due to their excellent thermal stability.

In a solar tower, the receiver plays a critical role in determining the plant's lifespan. It serves as the intermediary between the concentrated solar flux and the heat transfer fluid. The receiver can handle a flux of approximately 850kW/m2 and can achieve an outlet temperature exceeding 600°C for a liquid receiver and 700°C for a gas receiver.

Spectrally Selective Absorber Coatings (SSACs) of high performance have garnered significant interest in recent years. However, an unfavourable balance exists between conversion efficiency and thermal stability, which hinders their commercial advancement. Infrared reflectors, made from highly reflective metals like Cu, Al, Ag, and stainless steel, often exhibit instability at elevated temperatures (above 400°C). For operations at elevated temperatures, refractory metals like W, Mo, and Zr have been utilized in absorbers, but strong IR reflection remains unavoidable. In reality, SSACs continue to face issues such as surface detachment, oxidation, and interlayer diffusion. To develop metal/ceramic solar selective coatings with exceptional long-term thermal stability at high temperatures, one approach involves modifying the substrate. This can be done by depositing a barrier layer, inducing surface oxidation on stainless steel, or opting for a non-metallic substrate to prevent the diffusion of substrate elements. Another strategy is to introduce more stable metal components (TiN, WTi, WNi) or highly stable dielectrics (YSZ, HfO2, Si3N4, etc.) for absorbers. For nano-composite metal-dielectric coatings, it is reported that the highest efficiency at the high temperature is achieved by the low-index NC with nanoparticles on an infrared reflective flat Cu substrate, for both Cu and Ni NPs. For transition metal nitrides coatings, some researches have been focused on introducing silicon and carbon elements, or transforming transition metal nitrides into transition metal oxides. Furthermore, transition metal nitrides like TiN and ZrN could provide highly reflective properties in the infrared region similar to Au when containing excess nitrogen, so it provides the possibility to design higher-temperature (>700°C) all-ceramic absorbing coatings with binary ceramics (Al2O3, SiO2, Si3N4, ZrO2, HfO2, etc.) as diffusion barriers or anti-reflection layers, and oxynitrides or nitrides (ZrNO, TiNO, TiAlN, etc.) as absorptive layers.

Picture 7: Design of all-ceramic SSAs and characterizations of each layer; The measured absorptance spectrum of all ceramic SSA, the utilized solar radiation by the SSA, and the thermal emission spectra for a blackbody, the SSA at 1000K



Adapted from [28] Smith (2010, p. 284).

For Concentrated Solar Power (CSP) applications, the long-term stability of solar selective absorbers is crucial. This stability, in terms of microstructural, thermo-optical, and mechanical properties, ensures the durability of the receiver under extreme usage conditions. Researchers have subjected solar selective absorber coatings to a wide range of conditions, including varying temperatures (200-900°C), atmospheres (vacuum, air, O2 partial pressure), durations (from 30 minutes to thousands of hours), and periods (constant or slow/fast cyclic thermal load). The primary objective was to study the stability of optical properties, which can be affected by thermally induced phenomena such as oxidation, diffusion, and microstructural changes.

Spectrally selective absorbing coatings can typically be categorized into five types based on the structure of the coatings and the absorption process. In fact, numerous innovative selective absorbing coatings are composed of combinations from these categories. A coating may exhibit both particular scattering and semiconductor/metal tandem properties. Based on the different dielectrics, we aim to categorize high-temperature Spectrally Selective Absorber Coatings (SSACs) into three types: double cermet solar selective coatings, transition metal nitride multilayer coatings, and transition metal oxide multilayer coatings. Given their high conversion efficiency and high-temperature stability, some innovative double cermet solar selective coatings, such as WNi-Al2O3, WNi-YSZ and WTi-Al2O3, are potential candidates for solar thermal conversion at 600°C due to their exceptional long-term thermal stability. When it comes to transition metal nitride multilayer coatings, their superior mechanical properties and thermal stability are largely due to the layers that make up the coating. Coatings that are derived from MoN or HfN, including AlMoN, AlHfN, and HfMoN, may be better suited for elevated temperatures. Furthermore, the integration of silicon and carbon elements can boost the thermal stability of transition metal nitride absorbers.

To meet the demands of next generation Concentrated Solar Power systems (CSPs), transition metal oxide coatings are beneficial in averting failures at high temperatures, particularly those due to oxidation. Given their high efficiency, elevated operating temperatures, and significant potential for cost-effective production, the all-ceramic Spectrally Selective Absorber (SSA) could potentially expedite the rollout of next-generation CSP plants.

Conclusion

The article explores the application of coating technology on solar receivers in tower solar power plants to enhance thermal performance and durability. It examines the microstructure, surface characteristics, and thermal properties of coated solar receivers using advanced techniques such as SEM and XRD. Coatings play a crucial role in protecting materials from wear, corrosion, and oxidation at high temperatures. The materials used range from cermets and metal alloys to polymers and composites, with methods like HVOF spraying providing durable surfaces for extreme applications. In solar power towers, receivers are key components that convert solar radiation into thermal energy. Various types of spectrally selective absorber coatings (SSACs) are essential for improving efficiency and thermal stability. Some of the most promising solutions include double cermet coatings, transition metal nitride multilayer coatings, and multilayer oxide coatings. These have demonstrated high resistance to temperatures above 600°C, reducing degradation from oxidation and diffusion.

In conclusion, the development and optimization of spectrally selective coatings are essential for the next generation of concentrated solar power (CSP) systems. High-temperature stable coatings with improved efficiency can accelerate the adoption and effectiveness of solar tower technology, contributing to more sustainable and efficient renewable energy solutions.

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