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High solar energy concentration with a Fresnel lens

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The high solar energy density achieved in our simple and cheap Fresnel installation has been used for several surface modifications of metallic materials. This equipment is a very useful tool to apply concentrated solar energy in the field of high and very high temperatures (1500–2000 K). These temperatures are achieved in a few seconds and usually the materials treatments are completed in minutes. Fresnel lens installation is a serious alternative to the conventional equipment for material treatment and even to the large solar installations. In this work we review the surface modifications produced by concentration of solar energy with a Fresnel lens.

1. Introduction

Solar radiation is concentrated by reflection or refraction through mirrors or lenses. The mirrors can be plane, called heliostats, or parabolic; the lenses can be simple lenses or Fresnel lenses (FL). Concentrators are used to improve the solar energy caption in specific applications.

In PV Solar Energy, FL have been used as concentrators for PV cells. The problem is that the lens energy distribution is not uniform over the whole cell, it has a hot spot that could damage the solar cell. However, in PV Solar Energy, FL have been studied to reduce the cost of PV electricity in systems located in remote areas [1], to reduce the cost of autonomous solar PV installations [2] and to develop sun high concentration solar cells [3].

There are several applications of Thermal Solar Energy that need high temperatures, so solar furnaces are used. Solar furnaces are classified (Table I) in primary and secondary: in a primary solar furnace there is only one optical system, so radiation is concentrated only once, while, in a secondary one, radiation is concentrated by a second optical component. The concentration values, and so the temperatures achieved, are different.

As Rodríguez studied in her doctoral thesis [4], high concentrated solar energy is a suitable energy source for superficial modification of metallic materials. This kind of solar thermal applications usually need high temperatures (1500–2000 K). She worked with two large solar installations, the Plataforma Solar de Almería (PSA) and the Institut de Science et de Genie des Materiaux et Procedes (IMP-CNRS) at Odeillo, and with a FL, performing steel hardening tests. As can be seen in Table II, the power densities achieved with the FL are in certain cases similar to the densities achieved in some large installations, so FL can be used to achieve the high temperatures required. Whereas the large solar installations take up a broad extension, a FL installation can achieve the same density power using a small area.

The high power density achieved with a FL installation is adequate for materials surface modifications. A FL installation is a serious rival (Table III) to the conventional materials treatments owing to its low cost and the energy source: processes are economic, fast and environmentally friendly.

2. Fresnel lens

In a lens, the refraction phenomenon is produced in the surface, while the bulk material between the two surfaces doesn't have any influence in the refraction. In 1748 Georges- Louis Leclerc had the idea of reducing lens weight and size acting on the lens surface, but it was a French mathematician and physicist, Augustin-Jean Fresnel, who built, in 1820 the first lighthouse using Leclerc's design.

The FL is a flat optical component where the bulk material is eliminated because the surface is made up of many small concentric grooves (Fig. 1). Each groove is approximated by a flat surface that reflects the curvature at that position of the conventional lens, so each groove behaves like an individual prism. There are two basic FL configurations: linear (Fig. 2) and circular (Fig. 3). A linear FL has linear parallel grooves and the focus is a line. A circular FL has circular concentric grooves and the focus is a small circle.

FL manufacture processes have developed. First designs were cut and polished in glass. In 1950 they started to be made by pressing hot glass in metal molds, and since the eighties they are made of plastics. Modern plastic FL, cheaper and lighter than a conventional lens of the same size, have high optical quality and no spherical aberration.

TABLE I Solar radiation concentrators

Primary concentrators	Secondary concentrator
Direct furnace	By reflexion
Lens	By refraction
Parabolic mirrors	
Tower and heliostats field	
Indirect furnace	
Heliostat with parabolic mirror	
Heliostat with parabolic mirror out axis	

TABLE II Several solar installations

Country	Solar furnace	Density (kW)	Power density (Wcm $^{-2}$)
Spain			
Almería (PSA)	Tower and heliostats	3362	250
	Tower and heliostats	7000	250
	Heliostat and parabolic mirror	60	800
Madrid (CENIM)	Fresnel lens	0.05	260
France (Odeillo)	Heliostat and reflector out axis	1000	1600
	Heliostat and vertical parabolic reflector	6.5	1500

TABLE III Some technologies employeed in surface materials modifications

Technology	Treatment surface (cm^2)	Temperature at surface (K)	Power density (Wcm^{-2})	Power (kW)
Laser CO_2	<1	>5000	10^3–10^6	2–5
Laser Nd-YAg	<1	>5000	10^5–10^9	≈ 0.5
Plasma	≈ 100	>5000	10^4	10–2000
Solar Furnace	≈ 1000	≤ 3500	10^3	≤ 1000
Fresnel lens (CENIM)	0.20	≤ 1500	260	0.05

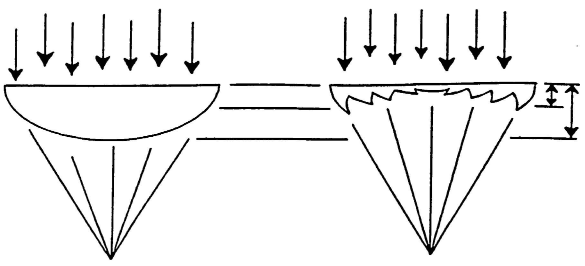

Figure 1 Conventional and Fresnel lenses.

The application of the FL determines the wavelength range of operation and the lens material. There are lenses designed to be used with near infrared, visible and ultraviolet. Lenses that work in visible range are made of acrylic, rigid vinyl or polycarbonate. The most suitable material will be the one that keep certain physical properties needed as thickness, rigidity, service temperature, weatherability, etc.

FL have many applications, and we use them daily: traffic signals, theatre focus, slide projectors, rear windows of cars, photographic flash, etc... FL can act as collimators, collectors, condensers, field lenses, magnifiers, for imaging, thermometry and solar energy collection.

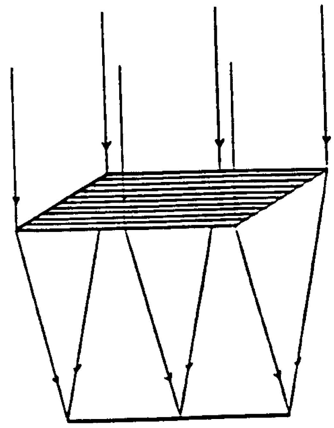

Figure 2 Linear Fresnel lens.

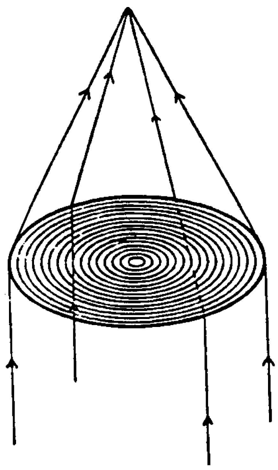

Figure 3 Circular Fresnel lens.

3. CENIM's Fresnel lens

In CENIM there is a FL that is used for materials surface modification. It is made of acrylic material and its specifications can be seen in Table IV. The lens was supplied by Edmund Optics Ltd. It is a planoconvex circular FL with its grooves toward the focus. The lens was characterized by Sobrino [5]: it has a circular focus of 5 mm diameter and if it is positioned perpendicular to solar radiation the power density at the focus is 260 Wcm^{-2}, it means that the lens concentrates 2644 times the incident solar radiation over the lens surface. Fig. 4 shows FL concentration factor versus distance to focus in two axis perpendicular to optical axis.

TABLE IV CENIM Fresnel lens specifications

Lens specifications	
Diameter	889 mm
Thickness	3.17 mm
Focal distance	757 mm
Grooves	50 in 25 mm
Refractive Index	1.49
Transmission	92% from 400–1100 nm

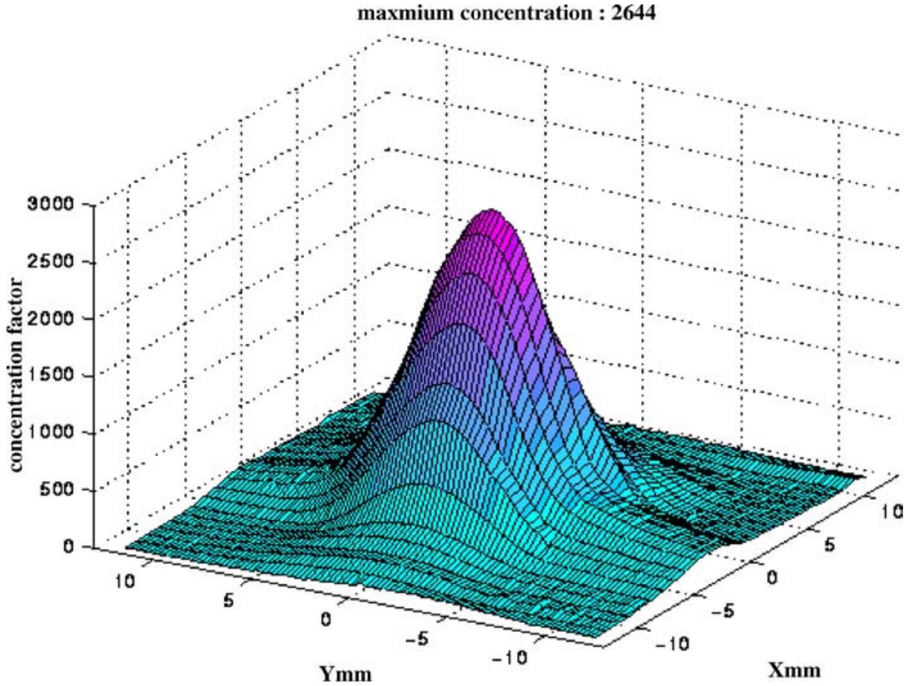

Figure 4 Distribution of concentration factor around the focus position.

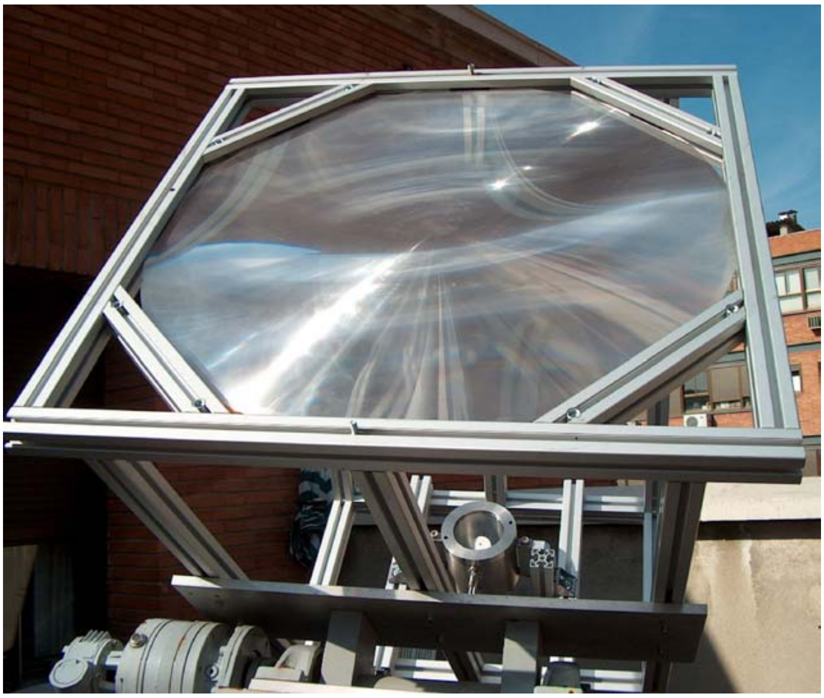

Figure 5 Fresnel installation at CENIM.

The lens is built into an aluminium installation designed by us (Fig. 5). The installation has a polar axis. The movement from east to west is controlled automatically by a computer and the solar height is hand positioned. Usually we work one or two hours before and after solar midday depending on the weather station.

Before the experiment starts the lens is positioned perpendicular to solar beams. It is covered except for a little circular area that allows focus the lens. Once the lens is focused it follows solar tracking. From this moment the installation is ready for doing the experiments. The lens is uncovered during the materials tests.

The installation was designed with a reaction chamber. This chamber is a stainless steel cylinder. It has a screw top that fit a quartz window, where the concentrated solar radiation comes into the chamber. Samples are located at the focal distance, inside the chamber. The reaction chamber has gasses inlet and outlet for controlling the atmosphere. The materials temperature can be measured with a thermocouple that is introduced through a little hole in the chamber.

This FL installation is very interesting because of its low cost. The lens is the cheapest part, while the most expensive component is the equipment to follow the sun's movement.

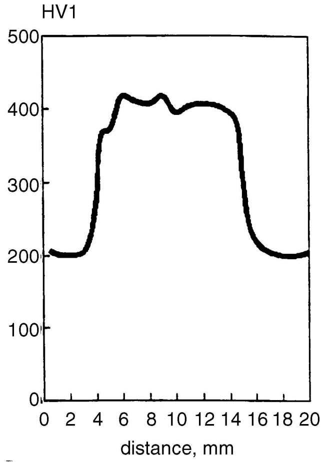

Figure 6 Distribution of Vickers hardness in the quenched sample.

4. Materials surface modifications with CENIM's Fresnel lens

Solar energy concentrated by a FL has been used in CENIM for several surface modifications in metallic materials: thermal treatment of steels, stainless steel and cast iron, gaseous nitriding of Titanium alloys and coating processes by self-propagating high-temperature reactions. The processes are short because high temperatures are quickly achieved.

4.1. Surface hardening of steels

Rodríguez *et al.* [6, 7] used concentrated solar energy with a FL to produce surface hardening on martensitic stainless steel (AISI 420) sample. Samples were cylindrical with 5 mm thickness and 35 mm diameter. Tests were performed at three temperatures (1193, 1263 and 1283 K) and after reaching the treatment temperature the samples were cooled in cold water. The profile of hardness (Fig. 6) in a track just under the exposed surface, about 0.5 mm, shows the spot of the concentrated beam (10 mm). Treatment times were about 100 s.

4.2. Gaseous nitriding of titanium alloys

García *et al.* [8] used for the first time solar energy concentrated by a FL to obtain titanium nitride films. The surface of cylindrical specimens of chemically pure titanium, 10 mm in height and 12 mm in diameter, were heated by the concentrated solar energy. The titanium was placed in the reaction chamber in which nitrogen is introduced. Fig. 7 shows a transversal view of the nitrided coating obtained with a treatment time of 120 s. The nitrided layer is uniform across surface and neither pores or cracks are observed.

The thickness of the layer is about 6 μm, which means a mean rate of 180 μm/hour. That is a very high rate compared with other nitriding processes (reactive evaporation, reactive sputtering and pressure nitriding) and similar to the induction furnaces and high power laser.

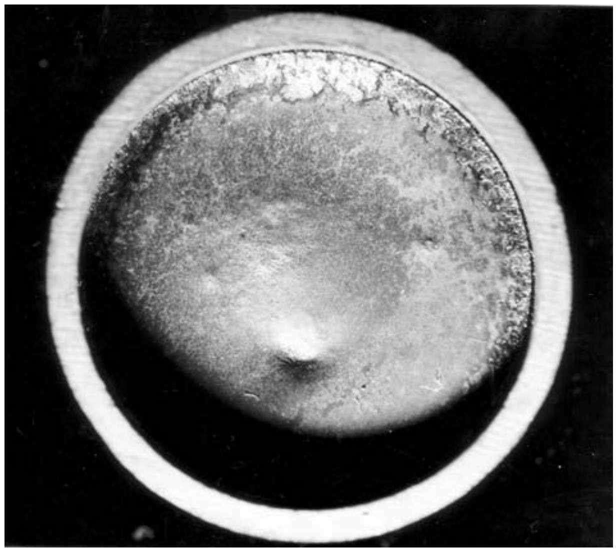

Figure 8 Coating of NiAl on steel (×4.5).

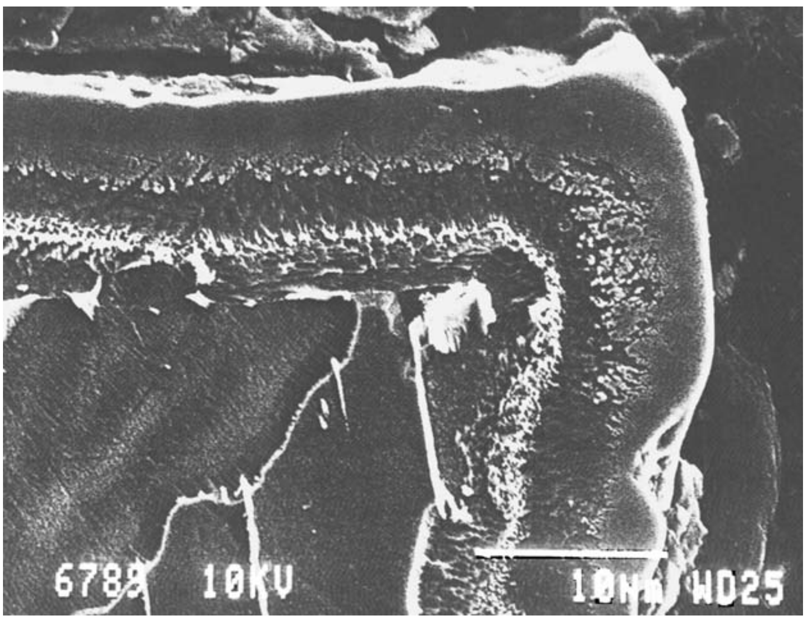

Figure 7 Titanium nitrided films.

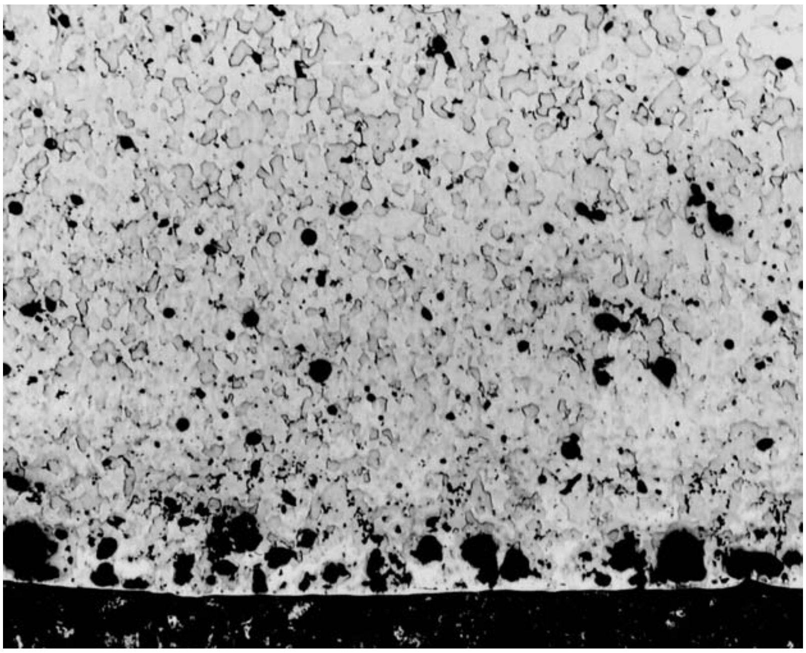

Figure 9 Grains of NiAl coating.

4.3. Coating processing by self-propagating high-temperature synthesis

Self-propagating high-temperature synthesis (SHS) is ignited by a high heating rate on a localized area of the sample. When this area reaches the ignition temperature the reaction starts in the sample. The reaction is highly exothermic: the high energy released propagates the reaction trough the whole sample.

Nowadays we are producing by SHS NiAl coatings on steel [9–11]. The reaction is started with solar energy concentrated by the FL. Concentrated radiation heats locally the sample, and about 30 s later the SHS starts producing the NiAl coating (Fig. 8). Fig. 9 shows NiAl grains and pores in a coating obtained.

5. Conclusions

Fresnel lens at CENIM is a small installation comparable to large solar installations due to the high power density achieved, needed for some kinds of materials treatments.

Solar energy concentrated by Fresnel lenses is a cheap and environmentally friendly energy source suitable for surface materials treatments. The advantages of the Fresnel installation make it a serious alternative to some conventional techniques used in this field.

Acknowledgements

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