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Experiences and Proposals for the Application of Concentrated Solar Energy in the Processing of Materials

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Abstract: Different experiences described are related to research works based on the application of concentrated solar energy (CSE). The experiences described are associated with quenching processes, layer generation processes by means of powder melting (cladding), self-propagated synthesis to obtain intermetallics, the formation of nitride layers of titanium in an atmosphere of Nitrogen, nitriding of steel and cast iron, the sintering of metals and ceramics, some processes of reduction of oxides and of welding, allotropy of metallic solid solutions; every one using CSE as the heat source. There are also experiences related to hybrid heat source processes such as electric induction and CSE hardening. At the end of the description, an evaluation of all these possibilities is carried out and proposals are issued on those that seem most promising and viable at this time.

We believe that CSE has a very promising future as an important resource to be used in industrial processes according to the needs of a better environment, as a relevant way to reduce energy consumption taking advantage of the unique opportunities offered.

Key words: solar energy assisted processes, low environmental impact manufacturing proposals

1. Introduction

Given the international energy situation and the convenience of greater use and exploitation of renewable energy sources, it is a priority to promote additional and alternative applications. A particular relevant type of energy for countries such as Spain and Mexico, due to the high potential that both have, is solar energy. Solar radiation, as Vázquez points out in [1] "is a form of energy that can be used as thermal energy, which has been used since ancient times to dry fruits, vegetables, obtain sea salt, etc.".

There is a radical significance for the energy if the origin is a renewable source or if it comes from fossil fuels. From the point of view of its application, it is relevant the magnitude of the energy available and the temperature of its source; radiant, coming from a fluid that heats by convection, or from solids, as it is transmitted by conduction. Among the group of renewable energies, solar energy has had a very high increase in use over the last half century, for all applications of medium and for high and very high temperature; not only for the conventional applications of low temperature as obtaining salts by evaporation of water or for drying diverse products.

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The concentration of solar energy is done by refraction or reflection optical systems. The classic concentration done using magnifying glasses is performed with Fresnel lenses of polymeric material of various sizes from small sizes, i.e., 400×400 mm, up to 1110 mm in diameter and 1300 mm of focal length with which it is easy to overcome the 1300 K.

Other devices to concentrate solar energy are those having reflecting surfaces as mirrors; this devices can have different designs according to their application. Classical are the old paraboloids used during the Second World War from 1000 to 1500 mm in diameter with the ones, temperatures in the focal area of 2,500 K can be obtained.

The advantages of parabolic concentrators are that high temperatures that can be obtained in the focal spot allow to reduce treatment times to obtain full transformation of many chemical and metallurgical processes. The dimensions can be the size of a satellite dish with which equivalent temperature magnitudes are achieved. In applications for Stirling engines, parabolic concentrators up to 5 to 9 meters in diameter are common.

The so-called Fresnel lenses are mounted on a solar tracker with a polar orientation; with these devices temperatures of up to 2273 K can be reached, with power densities near 2500 kW/m^2 [2]. An example of this type of solar concentrators is illustrated in Fig. 1. Using Fresnel lenses of 800 mm in diameter, many tests have been carried out to demonstrate the industrial potential of concentrated solar energy.

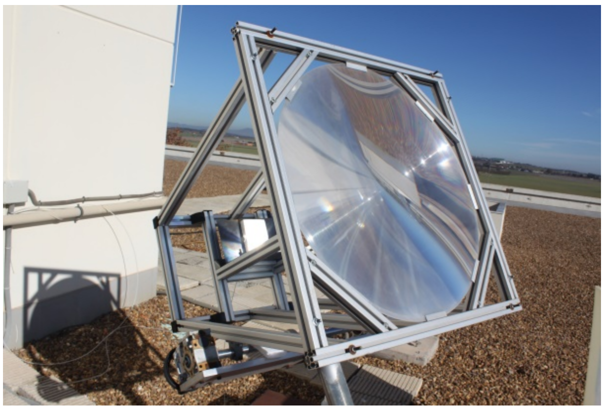

Fig. 1 Solar concentrator using a Fresnel Lens.

A knowledge field that for some years has begun to receive more attention and interesting developments is the use of CSE for heat treatment and processing of materials. Different reviews on the field can be found in Refs. [1-3]. Beside promising results, many initial experiments were done for superficial quenching treatments (Fig. 2) of various carbon and tool steels [4], with very good results.

An objective for the application of CSE in metallurgy is to substitute conventional methods and an option that has been achieved is to generate coatings resistant to corrosion through the fusion of powders by using ESC, for example, of austenitic stainless steels, placed on substrates of carbon steels, which is known as cladding [5].

By using CSE, it has also been possible to contribute to the activation and kinetics of various chemical reactions on material surfaces, which has allowed to obtain coatings of titanium nitride (TiN) using a Fresnel lens on an aTi6Al4V alloy (Fig. 3) [6] or to produce a coating of intermetallic NiAl compounds, through a self-propagated high temperature synthesis reaction [7]. This type of coatings have special interest for use in applications at high temperatures (Fig. 4).

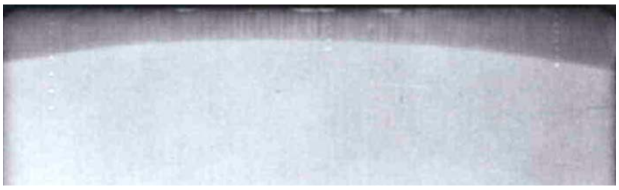

Fig. 2 Evidence of the quenched zone of a carbon steel after CSE heating and water quenching [4].

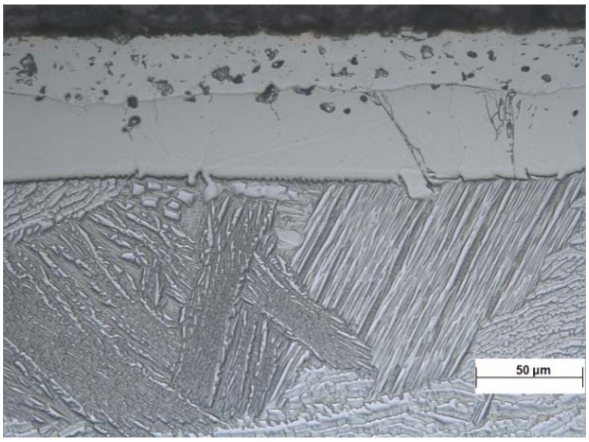

Fig. 3 Metallographic cut of TiN obtained using CSE [6].

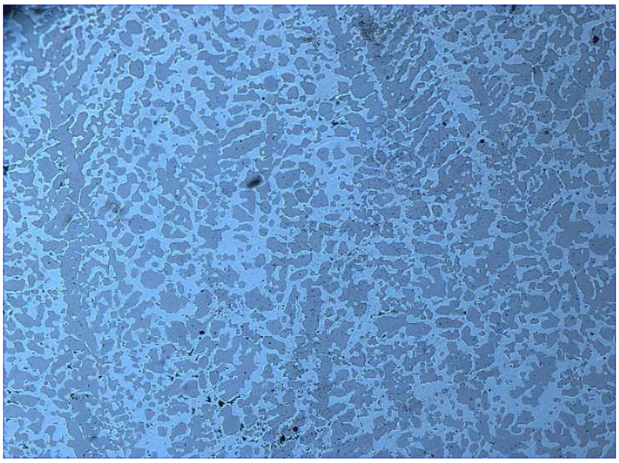

Fig. 4 Cladding of a NiAl over a carbon steel substrate using CSE. Dendritic microstructure of the NiAl coating [7].

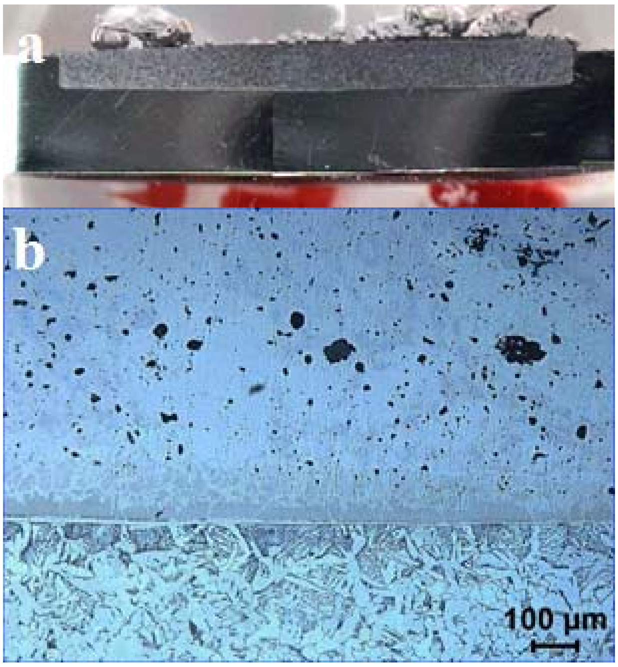

Fig. 5 a) NiAl coating on steel substrate obtained by a CSE-SHS (self-propagating high temperature synthesis process with concentrated solar energy) b) NiAl-steel interphase in detail [7].

Other research applications of CSE are the gaseous nitriding of a Ti6Al4V alloy [8] and the nitriding of a ductile iron, using molten nitrates salts; obtained the latter in significantly shorter times than those used in industrial processes [2].

Also linked with the field of bonding methods related to surfaces, we can highlight the successful works in which weldings have been obtained using CSE for different materials [9, 10] (Fig. 6).

In other materials processing techniques, it is worth mentioning research aimed at evaluating the possibilities of melting aluminum (and other materials) or extruding aluminum, using CSE [11]. Likewise, the experiments that allowed to obtain a steel for AISI M2 tool reinforced with particles of vanadium carbide (VC), using sintering technologies by means of CSE [12] are also noteworthy.

Recent experiments have been done related to the reduction of oxides, for example the reduction of iron oxides (Fig. 7) and even, the oxidation of metals of high melting point such as tungsten.

In the review of the possibilities of applications of the CSE, we highlight the ones reported by Rojas-Morin, Barba-Pingarrón and Alvarez-Brito [13-17]. In the evaluations described, modeling and simulation techniques are used to prepare and to corroborate experimental developments, with the objective of understanding to a greater extent the processes of thermal fatigue that nickel-based alloys and stainless steels can experience in central tower systems. Also based on previously described, select alternative materials or propose strategies for their best response to this condition is prospected. This research works are aimed at determining the evolution of temperatures and thermal stresses that can occur when heating different materials using CSE.

2. Hybrid Heat Treatment System through Induction and ESC

The recent work of Rojas-Morín et al. [16] is aimed at generating hybrid systems, i.e., in the case of induction heating processes (as in the quenching of a steel) added to heating by CSE. In Fig. 8 a detail of the device with a Fresnel lens and an induction heating coil can be observed. In the first experiences, it has been possible to reduce the energy consumption and reduce the process time, and now it is planned to work in other temperature ranges and continue evaluating the potential of the system.

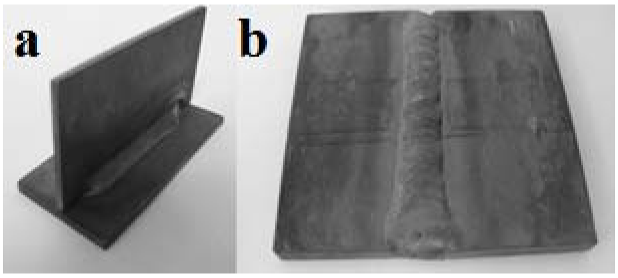

Fig. 6 Steel welding a) and Ti alloy welding b) using CSE [9, 10].

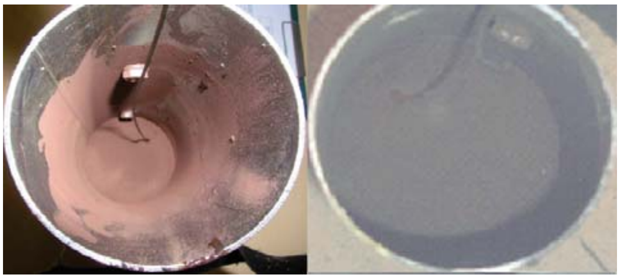

Fig. 7 Hematite to magnetite reduction using CSE [2].

Fig. 8 Image of a hybrid induction-CSE heating system for material processing. UNAM [16].

3. Theoretical and Experimental Study of Stainless Steel AISI 316 Submitted to ESC and its Post-Qualitative Evaluation

Phase transformations with application of CSE allow accelerated treatments around the thermally assisted treatments and reduction of costs for manufacture. However, benefits in this sense can be harmful when it is necessary that materials in the devices have a life service as long as possible. Phase transformations for metallic materials may lead to the degradation or even loss of the initial desirable mechanical properties and chemical stability.

In the experiment of Alvarez-Brito [17], conducted in the months of October and November 2015, an exposure of austenitic stainless steel AISI 316 specimens of similar geometry of the pipes of the solar central tower receivers (i.e., internal and external radii) was carried out to the concentrated solar radiative flow in the solar furnace of high radiative flow (HoSIER) of the UNAM, in Temixco, Morelos, México. The material was chosen because it is among the lowest cost and that it is employable for the application of pipelines in solar receivers with thermal fluid transport. The objective of the development was to later determine qualitatively the effects of the cyclic exposition to CSE.

Prior to the experimentation, a numerical simulation of the radiative and thermal stress fields was carried out using the COMSOL MULTIPHYSICS® software, in order to determine the parameters for the subsequent experimentation. The model started from the ray tracing made with NREL SolTrace® software to obtain the information of magnitude and distribution of the concentrated radiative flow as illustrated in Fig. 9; then, Fig. 10 shows an example of the interpretation of the CSE flux over the pipe in the simulation, which turns out to be very similar, later, to the field of thermal stresses.

Four AISI 316 austenitic stainless steel specimens were exposed to thermal cycles respectively performed using CSE, to achieve operation temperatures of solar central tower receivers. Fig. 11 shows one of the specimens during its exposure.

To qualitatively determine the effects of these experiments using CSE, a scanning electron microscopy

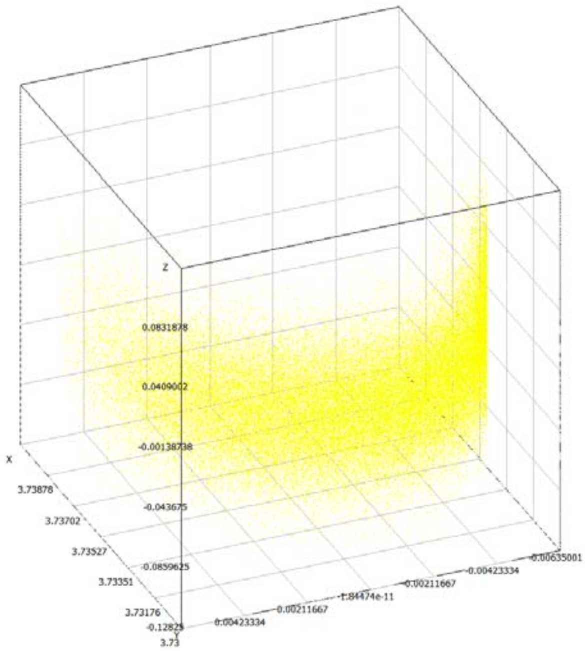

Fig. 9 NREL SolTrace® ray intersection model, over a cylindrical shape receiver; this model involves the concentrator optical behavior of the HoSIER in UNAM.

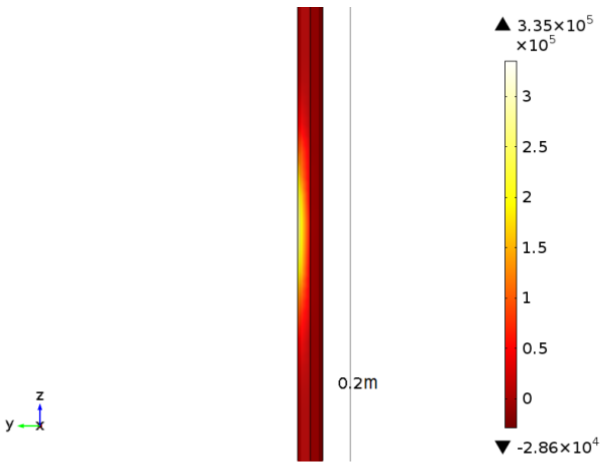

Fig. 10 Radiative flux over cilindric specimen at 50 mm behind focal point in the HoSIER, UNAM [17].

Fig. 11 Specimen exposure of a stainless steel specimen to CSE in the HoSIER [17].

(SEM) observation and an energy dispersive X-ray spectroscopy (EDS) were performed. Fig. 12 shows the EDS performed in a test tube without exposure to the CSE cycling in the HoSIER, while Figs. 13 show the differences generated as effect of application of the cycles with CSE.

Subsequently, the four specimens were subjected to X-ray diffraction (XRD) and to a selective metallography in order to detect the present phases. With both techniques the development of the δ-ferrite phase has been verified. This phase does not appear at such test temperatures with conventional heating methods (as demonstrated with one of the test and comparison specimens); so that an activating effect of the CSE can be concluded.

4. Obtaining Metal Coatings Assisted with ESC

Another research in development is the generation of NiAl coatings by CSE (using Ni and Al powders), for

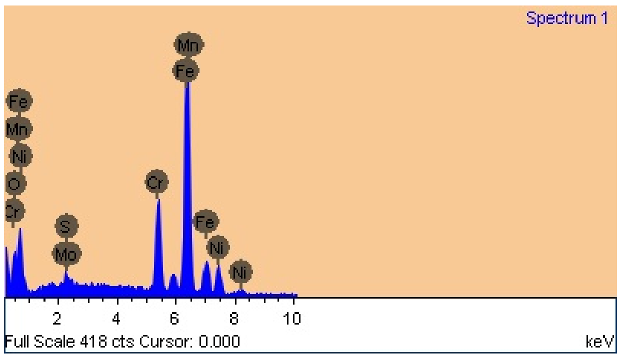

Fig. 12 EDS analysis over a non-exposed to CSE specimen, where no visible phase change by SEM observation was seen.

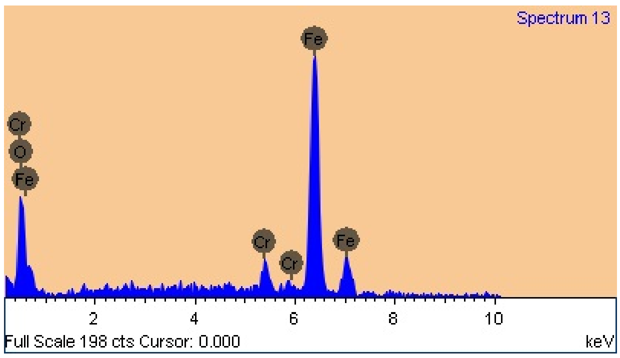

Fig. 13 EDS analysis over a visible phase change in SEM observation for a CSE treated specimen. The main difference is the absence of Ni.

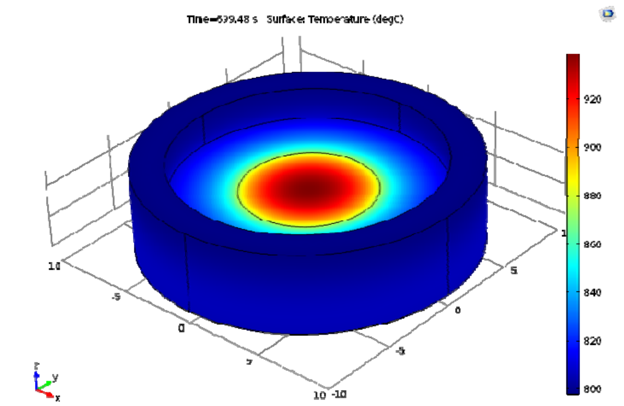

Fig. 14 Steel piece with NiAl powder treated with CSE simulation, considering transient and 3D characteristics.

special application of pieces used at high temperatures. In a first stage, simulations of the process have been carried out and a sample of it can be observed in Fig. 14.

5. Conclusions

The experiences that have been obtained in the application of CSE for the processing of materials allow us to glimpse with optimism perspectives in the future, given the important advantages it offers in terms of economic resources and benefits in fields such as manufacturing.

From the described experiences we propose the following comments and conclusions:

1) A possible drawback is the lack of continuity in the provision of the solar energy resource, which for many applications, it is a point of consideration for technological developments. However, alternatives such as hybrid systems can be proposed.

2) A current limiting aspect for CSE application technologies is the size of the pieces to be treated. In this case, it is considered that it will be necessary to develop systems that allow movement of the samples to be treated. With this, the apparent deficiency can be remedied.

3) In an initial stage it is considered that the contributions and valuable considerations that can be provided by the use of CSE are:

a) The possibility of producing very important energy savings by acting on hybrid systems for heating in a variety of industrial processes

b) The possibility of reducing the processing times in a relevant way, in various processes, as has been corroborated in cases such as the nitriding of steels or the reduction of oxides. This field, in turn, constitutes a challenge as a field of research in the immediate future.

c) The effects caused by the use of CSE in materials processing are also a limitation for the part of reception of energy in the systems, given the photo-activating capacity of the solar spectrum.

Acknowledgments

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