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Selection of high temperature materials for concentrated solar power systems: Property maps and experiments

D.G. Morris [a,*], A. López-Delgado [b], I. Padilla [b], M.A. Muñoz-Morris [a]

[a] Department of Physical Metallurgy, CENIM-CSIC, Avenida Gregorio del Amo 8, E-28040 Madrid, Spain
[b] Department of Primary Metallurgy and Recycling, CENIM-CSIC, Avenida Gregorio del Amo 8, E-28040 Madrid, Spain

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Abstract

Concentrated solar power systems are receiving increasing attention as electricity generating systems, whereby the sun's heat is focused onto a receiver heated to high temperatures. Systems operating today are generally limited to temperatures below about 600 °C, but there is considerable interest in increasing operating temperatures, with heat receivers generally constructed using refractory metallic alloys or ceramics. The present study compares the behaviour of a range of metallic or ceramic materials with advanced intermetallic alloys which have been developed for high-temperature aeronautic or power-generating systems. A few experiments are reported using intense solar heating to demonstrate the damage that may be sustained, depending on the material that is considered. Accelerated cyclic oxidation experiments further emphasize the sensitivity of the various materials to oxidation and thermal damage accumulation. The important characteristics required of the material to be used for the receiver are described and used to generate property maps where the suitability of different classes of materials (metal, intermetallic, ceramic) may be compared. Depending on the precise conditions of where the receiver will operate, and whether creep, fracture or oxidation/spalling is the most important damaging process, either refractory Ni-base alloys, Mo-silicides, or ceramics may be the best material for the application.

Keywords: Intermetallics; Nickel based superalloys; Ceramics; Failure

1. Introduction – Concentrated solar power systems

There is increasing interest in the use of solar energy as a heat source for electrical power generation (Avila-Marin, 2011; Franchini et al., 2013; Kalogirou, 2014). The sun provides an energy density of up to 800 W/m^2 at moderate latitudes, with deserts offering ideal locations for power generating systems in most continents. Concentrating the solar power by factors of up to 10^4 leads to power densities of the order of 1 kW/cm^2, similar to values achieved by industrial CO_2 power lasers used for materials processing. Such high solar power densities can be used for heating receptors to very high temperatures for power generation, or for surface processing of bulk or powdered metals and alloys (Sierra and Vazquez, 2005).

The last decades have seen significant improvements in the design and selection of materials for such concentrated solar power systems and electrical power costs are falling to become competitive with wind-turbine power generation. One of the most important trends has been the change from so-called trough systems, whereby the sun's energy is concentrated by a long, linear parabolic mirror onto a tube receptor at the focal line, to the so-called power tower concept, whereby a wide array of small mirrors called heliostats focuses the energy onto a relatively small area

* Corresponding author. Tel.: +34 91 553 8900; fax: +34 91 534 7425.
E-mail address: david.morris@cenim.csic.es (D.G. Morris).

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where a receiving component is found (Avila-Marin, 2011; Franchini et al., 2013; Kalogirou, 2014). An illustration of such a power-tower solar power generating system is given in Fig. 1. Some indication of the interest in such power systems is the installed generation capacity, which is of the order of 10 GW worldwide, with more than 2 GW in Spain, for the trough generators, and about 1 GW worldwide, with about 50 MW in Spain, for the more modern power tower generators (Avila-Marin, 2011; Franchini et al., 2013; Kalogirou, 2014; Rojas-Morin and Fernandez-Reche, 2011). With the continuing concern for energy supplies (especially in countries like Spain) and atmospheric CO_2 emissions, these concentrated solar power generators promise an attractive future.

The receiving tubular component of the solar power tower is a heat exchanger where the solar energy is used to heat some fluid which extracts the heat to a steam generator for electricity production. While the trough systems have generally used air or oil as fluid, heated to temperatures of the order of 300 °C, the power tower systems achieve much higher power densities, and use hot air or gas, molten salts or metals (e.g. Na) for heat transfer. In commercial systems, the receiver temperature is typically limited to below about 600 °C because of problems of material durability. This increased temperature is a major reason for the improved energy efficiency of the power tower concept (Avila-Marin, 2011; Franchini et al., 2013; Kalogirou, 2014). The drive for higher efficiency is leading to the evaluation of experimental systems where much higher temperatures are achieved, reaching temperatures near and above 1000 °C (Avila-Marin, 2011; Franchini et al., 2013; Kalogirou, 2014; Rojas-Morin and Fernandez-Reche, 2011; Pierrat et al., 2011; Boubault et al., 2012, 2014). While commercial systems use receivers of refractory alloy such as an Inconel alloy, or a ceramic such as SiC, the very high temperatures lead to problems of microstructural evolution, creep degradation, thermal fatigue (Rojas-Morin and Fernandez-Reche, 2011), or degradation of absorptive coatings (Boubault et al., 2012, 2014). Oxidation can become a problem at very high temperatures, leading to the consideration of improved ceramic materials (Pierrat et al., 2011). Many of these problems – degradation of microstructure and general mechanical properties, creep or fatigue damage, oxidation or corrosion for the given environment – are similar to those encountered in other thermal power systems (Schulte-Fischedick et al., 2007; Nickel et al., 1986; Yvon and Carre, 2009; Khare et al., 2013), for example Externally-Fired Combined-Cycle gas or biomass combustion systems, Integrated-Gasification Combined-Cycle systems or Solid Oxide Fuel Cells (Schulte-Fischedick et al., 2007), or nuclear power reactors (Nickel et al., 1986; Yvon and Carre, 2009; Khare et al., 2013), where the drive to higher temperature capability has led to significant materials research.

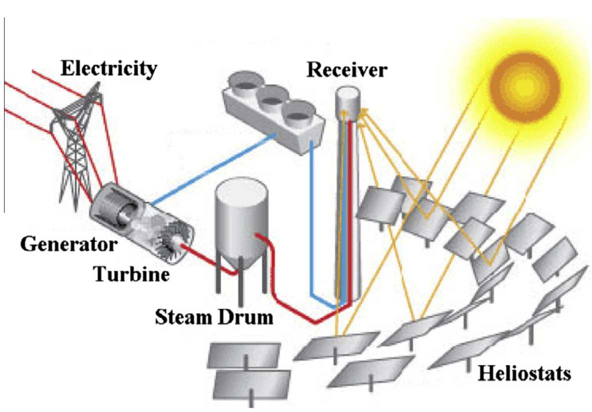

Fig. 1. Schematic illustration of a Concentrated Solar Power System using the sun's radiation for electricity generation. An array of reflecting mirror heliostats focuses intense solar heat onto the receiver at the top of a tower. The receiver acts as a heat exchanger, transferring heat to a suitable fluid (molten salt, oil, etc.) which is used to generate steam and power a turbine.

The material used for the receiver must possess a wide range of physical, mechanical and chemical characteristics. It should have good thermal conductivity, suitably low expansion coefficient, and for some receiver constructions be transparent. It should have sufficient Creep Resistance for the high temperatures, depending on the construction and the forces imposed, as well as sufficient toughness for varying temperature operation. It should resist oxidation or corrosion, depending on the atmospheric or salt/fluid environment. These requirements represent a severe challenge in the drive to optimise materials selection and permit significant increases in operating temperature.

The present study examines the physical and mechanical characteristics of a wide range of ferrous and nickel-base refractory alloys that may be considered for use in high-temperature receiver applications. At the same time, the behaviour of these conventional materials is compared with that of advanced intermetallic alloys, which have received significant research and development effort as materials for components in aeronautic or power-generating equipment, especially inside gas turbines. Such intermetallics have been studied with these high-temperature applications in mind, but have not been previously considered for concentrated solar power systems, where similar conditions of high temperature, significant static and cyclic loading, and aggressive environments will be encountered.

The presentation here is separated into three major lines. First, some solar heating experiments are reported, which serve simply to demonstrate the important changes that can be brought about by concentrated sunlight. The significant differences of behaviour of various materials under such very severe thermal loading are thus illustrated. In a second stage, some accelerated cyclic oxidation studies are carried out at temperatures somewhat above those which can be expected for long term collector usage, and which emphasize the importance of both the oxidation behaviour and the thermal shock resistance in determining material response. In a final stage, a brief review of the most important materials requirements is presented, showing that it is the correct combination of various