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Thermomechanical testing under operating conditions of A516Gr70 used for CSP storage tanks

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ABSTRACT

Thermal energy storage (TES) in molten salts is the storage dominating technology in solar power applications today. In two-tank molten salt storage systems energy density ranges from 30 to 70 kW h/m^3 are achievable. The salt material used is a binary system, composed of 60% $NaNO_3$ and 40% KNO_3. In the 8 MWh_{th} pilot plant built and tested by Abengoa, the storage tanks were made of steel A516Gr.70 using the Appendix M of code API 650 for their design. A specific testing device was developed to evaluate thermo-mechanical properties, and a study was conducted in order to evaluate tensile properties of A516Gr.70 specimens under operation conditions for the hot tank at the pilot plant that is in contact with molten salts at 380 °C. Results confirmed the outcomes of the work: the reduction of the yield limit, elongation before fracture, and Young modulus at 380 °C after having been 5 min immersed in molten salts. Moreover, after a creep-test simulating operating 7 days conditions during, an additional reduction of the yield limit was measured.

1. Introduction

The global crisis of energy is one of the biggest challenges for the near future for researchers and policy makers in order to achieve a sustainable solution that deal with this energy crisis [1,2]. Solar energy is the highest power source of the world. Thereby, solar power technologies are able to produce high amounts of sustainable power. Concentrated solar power (CSP) plants [3,4] are systems able to concentrate a large amount of solar energy using different types of collectors; several characteristics of solar power plants are described by Desideri et al. [5].

Nowadays, thermal energy storage (TES) is a promising technology to be applied as a complement of CPS plants in order to reduce the gap between energy supply and energy demand [6]. Therefore, TES systems are implemented in CSP plants successfully by producing electricity several hours after sunrise [7]. Moreover, TES will help in making CSP much more viable and feasible from the economic and technical point of view. But the proper selection of materials has a great significance not only to deal with a proper performance of the plant but also for the economic interest of TES units.

A516Gr.70 steel was used to manufacture the storage tanks in the pilot plant of nitrate molten salts with 8 MWh_{th} built by Abengoa [8]. A516Gr.70 is the main used steel in commercial CSP plants due to its high mechanical performance efficiency under stress and its relative low cost. Mechanical design typically uses the yield strength as one of the main design parameters. However, it is well known that the mechanical properties of steels as the yield strength or the modulus of elasticity decrease with increasing temperature. In this study, this change is of extremely importance because during operation of both storage tanks, the cold one is designed to operate at 288 °C and the hot one at 388 °C. Moreover, the maximum service temperature is the highest temperature at which the material can be used for an extended period without significant problems [9]. For the majority of commercial carbon steels, this temperature ranges from 270 to 360 °C and only few grades of steel are certified to work at higher temperatures like the operation conditions of the hot tank of molten salts storage systems. Prieto et al. [10] previously reported a detailed description of the tanks design. Both tanks were built with steel A516 and two grades with different grain size. Thus, grade 60 with the smallest grain size was used for the tank cover and grade 70 for the rest of the tank. Parameters used for the design were those of the Appendix M of code API 650, although it only gives the requirements for working temperatures between 90 °C and 260 °C.

The study of the evolution of the mechanical properties with temperature may be performed varying temperature with special testing devices adapted for such purpose, and following international standards

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Table 1
Composition of Carbon steel A516 Grade 70 [12].

Composition	Content (wt%)
Fe (Iron)	Base Element (> 98)
C (Carbon)	.27
Mn (Manganese)	.79–1.3
S (Sulphur)	.025
Si (Silicon)	.025
Mechanical properties	
Ultimate tensile strength (UTS)	485–620 MPa
Yield Strength	260 MPa (minimum value)
Elongation	15% (minimum value)

for testing [11]. Nevertheless, the working conditions of this material in operation, which are the temperature (388 °C) and the environment (in contact with nitrate molten salts), are not considered in any standard. For this purpose, a study was conducted in order to evaluate tensile properties under operation conditions by testing in a device developed at the University of Barcelona, where a series of mechanical experiments were performed with A516 gr70 carbon steel specimens in contact with molten salts at 380 °C. Prior and after the mechanical testing, a metallographic study was performed.

2. Methods and materials

2.1. Materials

The specimens for this study were obtained from a plate of the same carbon steel used in the construction of the tanks at the Abengoa plant. Table 1 summarizes the main characteristics collected from the CES Selector database for the reference ASTM A516 Grade 70 Carbon Steel Plate for Boilers and Pressure Vessels.

Specimens for mechanical testing were machined from the original plate by laser cutting. The size of the specimens was calculated following the standard from the plate thickness [11]. Dimensions (in millimetres) and design of the specimens are shown in Fig. 1.

2.2. Experimental set up

A small furnace was designed and built at University of Barcelona to perform the tests at the desired temperature (in this case 380 °C), having the specimen in contact with nitrate molten salts during the mechanical testing. The mixture selected is the so-called *Solar salt* reported in the literature with a composition 60:40 $NaNO_3$ and KNO_3 by weight, close to the eutectic composition.

The cylindrical device was made of quartz, and its size allows testing the central part of the samples. A specific opening was designed to introduce a thermocouple to monitor the molten salts temperature as shows the scheme of Fig. 2.(a). The top and the bottom of the device are designed so that a refrigeration circuit using water as heat transfer fluid may be coupled, to prevent molten salts leakage. Furthermore, it also has the central part with a reduced section in which an electrical resistance was coiled around, see Fig. 2.(b), and then fully thermally insulated, see Fig. 3.

The insulated system keeping the length of reduced section of the specimen in contact with molten salts is presented in the upper right part of Fig. 3. The sample is then fixed through the jaws to the mechanical testing machine Incotecnic MUTC-200.

In order to evaluate the effect of temperature on the mechanical behaviour, three different experiments were performed.

First experiment: the material under study was first tested at room temperature. The tensile test was carried out at a loading rate of 5 mm min^{-1} until failure. Then, the conventional diagrams plotting stress (σ) vs. % strain (ε%), where stress and strain are defined with Eq. (1) and Eq. (2), were calculated:

$$\sigma(MPa) = \frac{F(N)}{S(mm^2)} \tag{1}$$

$$\%\ \varepsilon = \frac{\Delta l\ (mm)}{l\ (mm)} x100 \tag{2}$$

where *F* is the applied force (in *N*) and *S* is the area perpendicular to the application of force, in the case of the specimens tested it is 122.5 mm^2 and to calculate it, *l* is fixed to 205 mm, being the distance between jaws.

The yield strength obtained from the conventional diagram was used as a reference yield strength to perform the next mechanical tests

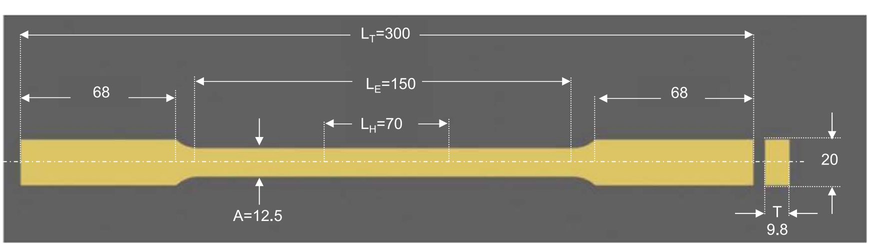

Fig. 1. Dimensions of the specimens machined from A516Gr70 plate [11].

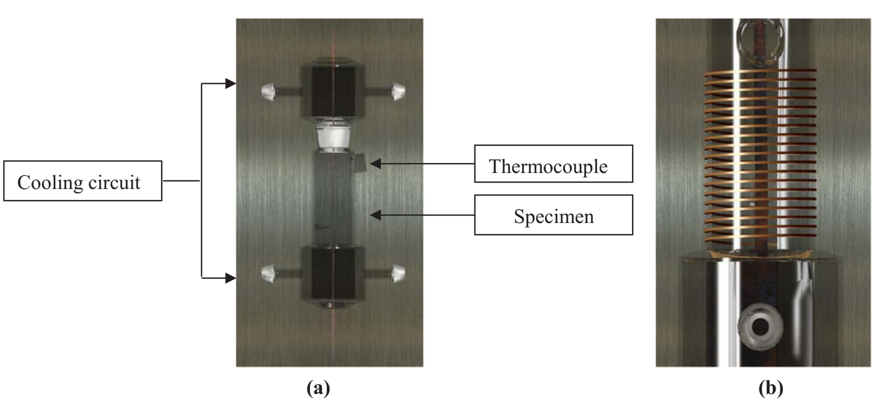

Fig. 2. (a) Small furnace devise; (b) Heating source.