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Experimental study and thermodynamic computational simulation of phase transformations in centrifugal casting bimetallic pipe of API 5L X65Q steel and Inconel 625 alloy

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ABSTRACT

In this work have been studied the phase transformations occurred during a cladding process by means of centrifugal-casting route used to produce a bimetallic pipe between an API 5L X65Q steel as backing material and Inconel 625 as corrosion resistance cladding alloy. Experimental measurements and computational thermodynamics calculations were developed aiming at characterization and understanding in the clad interphase phenomena. Thermodynamic calculations were performed by Calphad method to obtain pseudo-binary phase diagrams and kinetic simulations, allowing the quantification of interdiffusion phenomena occurred during solidification between the two alloys. Variations of chemical composition and crystallography along interface intended by Calphad calculations were contrasted with chemical microanalysis and nanoindentation measurements, as well as, optical (OM), scanning electron (SEM), and transmission (TEM), and atomic force microscopy (AFM) observations developed through the interface. Results show that a new interfacial region was formed presenting high hardness values with characteristics of a crystallographically transitional region, allowing the clad affixing.

1. Introduction

The cladding process consists of the metallurgical bonding between two materials with protecting purposes, wear and corrosion resistance. The protective material is deposited on a backing material named substrate, which provides the appropriate mechanical resistance. Commonly, there have been used as protective materials stainless steels, nickel alloys, and non-metallic materials like ceramics or polymers. On the other hand, materials for substrates includes high strength-low alloy (HSLA) steels and any other type of metal suitable for this performance [1]. Centrifugally-casting (Centricast) is a cladding method that involves casting molten metal into speedily rotating molds or dies, which has been extensively applied to produce clad pipes, tubes, and tubular components [2]. Petrochemical industries are the main consumers of centrifugally-cast pipe internally-cladded. Using Centricast process, it has been possible to manufacture bimetallic pipes, which are employed offshore to extract and transport oil, gas and other fluids in harsh environments, at lower cost as if manufactured entirely with corrosion resistant alloys.

Inconel® 625 alloy is a wrought Ni-based solid solution superalloy with excellent behavior to corrosion resistance, combining high strength and good fabrication characteristics [3]. Although this alloy was developed to service at temperatures below 973 K, it has been observed aging at range of temperatures 873 and 1073 K [4]. However, high production costs of entire pipes of Inconel 625 restrict the application of this alloy. Consequently, cladded of this Ni-based superalloy on an appropriate economical substrate is a useful solution to fabricate high corrosion resistance tubes and pipes [5]. One of the most widely used pairs of materials mild steels internally coated with Ni-based alloys [6].

Despite the cladding process between Inconel 625 and carbon steel has been studied [2], a low amount of information about phase transformation and mechanical properties is available. Verdi et al., [7] investigated the mechanical properties of small thickness clads Inconel 625 / low alloy steel obtained by cold spray (CS)

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and laser cladding (LC) processes. These authors using nanoindentation found LC process produced coatings hardness lower than CS, as well as, higher adhesion to substrate. Rajani et al. [8] studied the effects of process parameters in explosive cladding (EC) of bimetallic Inconel 625 / ASTM A 517 steel. Results of above mentioned investigation showed that characteristics related to bonding, defects and microstructure depends on used parameters. Additionally, a new region has been formed, which contents mix of elements of both materials; however, without the formation of intermetallic compounds. Rajani et al. [9] compared the corrosion behavior of clad Inconel 625 / ASTM 517 steel fabricated by explosive (EC) and fusion (FC) cladding. Authors observed that FC clads showed non-uniformity chemical distribution at interface region due to microsegregation of Nb and Mo, reducing their corrosion resistance compared to EC process.

Due to the high performance expected from cladded centrifugally-cast pipes, it is necessary to pay special attention to integrity in zones near to the fusion zone between dissimilar materials, where failures can occur preferentially, because of chemical composition, microstructure and melting points differences. Owing to complexity and costs of experimental observations aiming to study the diffusional phenomena occurred in centrifugally-cast cladding pipes, an alternative technique can be applied for to investigate this phenomenon: the use of thermodynamic computational simulations together with moderate experimentation. Calphad (Calculation of Phase Diagrams) method [10], has been used successfully to study solidification sequences, phase transformation, and chemical composition profiles in welded joints of low alloy carbon steels [11] and Ni-based alloys [12]. The goal of this work is to study the phase transformations occurred during a centrifugally-cast cladding of an API 5L X65Q steel and Inconel 625Ni-based alloy using computational simulation and experimentally measurements. In this investigation, it was carried out calculations of phase transformations using Calphad method with the aim to obtain compositional profiles, and to study the nucleation of intermediate phases at interface of clad. The metallurgical characteristics of bimetallic joining has been studied through characterization techniques such as nanoindentation, plus optical (OM), scanning electron (SEM), transmission (TEM), and atomic force microscopy (AFM).

2. Materials and methods

2.1. Experimental layout

Fig. 1 schematically shows the process chart through which simulations and experimental work was done. Aiming to establish conditions for Calphad calculations, it was necessary to determine a set of parameters and data. The chemical composition of materials measured by mass spectrometry before their pouring in the spinning mold is listed in Table 1. Cladded samples for metallurgical observations were extracted from centrifugally-cast process between Inconel 625/API 5L X65Q steel, which was developed using a rotational speed of 2074 rpm. The furnace loads of the API X65-Q material and of the Inconel 625 where prepared to achieve the desired thickness for both material in the pipe. The produced pipe dimensions obtained were 108 mm of external diameter OD (given by the diameter of the centrifugal casting mold), with 8 mm thickness for the API 5L X65Q, 9 mm of thickness for cladding Inconel 625 internal pipe and a pipe total length of 2374 mm. The inner diameter of the pipe was machined, aiming to obtain an entire thickness of 12 mm in the bimetallic pipe. Time of cast between both alloys was 50 s.

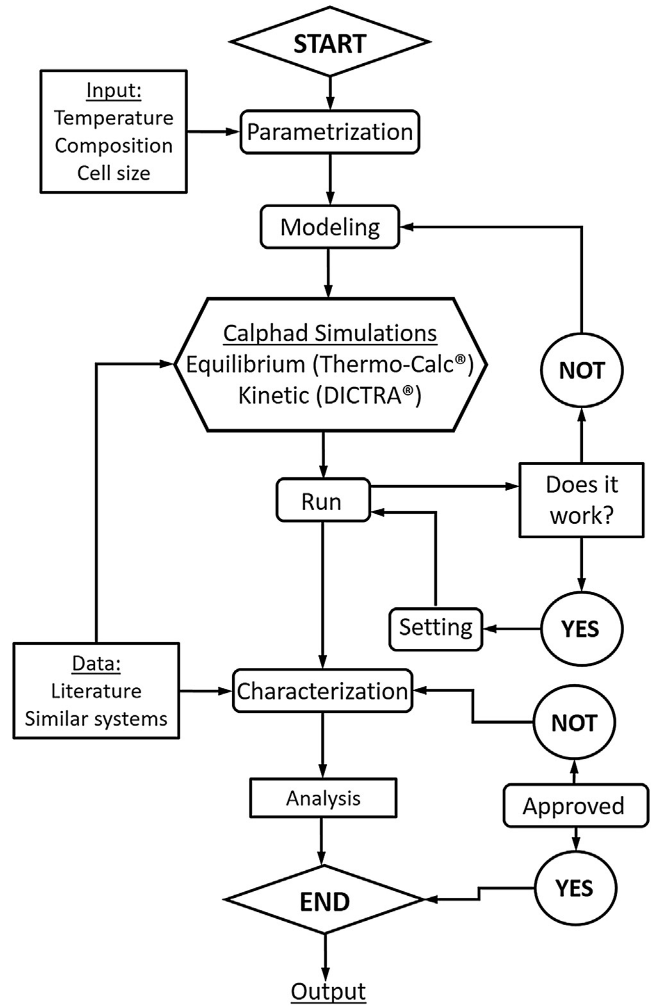

Fig. 1. Chart of process to perform simulation and characterization.

2.2. Thermodynamic calculations

Thermodynamic computational calculations were performed using Thermo-Calc® (TCC) software version 3.1 [13], for both API 5L X65 steel and nickel 625 alloy, to obtain pseudo-binary phase diagrams, mass percent vs. temperature and mass fraction vs. temperature. These diagrams were used with the aim of determining which phases may occur, and get the *liquidus* and *solidus* temperatures necessary to carry out the kinetic simulations. To perform the simulations, it was used the chemical compositions of alloys from Table 1. For pseudo-binary diagrams calculations, it was chosen the following phases: Liquid, BCC_A2 (BCC structure), FCC_A1 (FCC structure) and cementite for X65 steel and Liquid, FCC_A1 (FCC structures including matrix and MC carbides), M23C6 carbide and Laves for the Inconel 625. Temperatures values slightly above theoretical melting points were set for both alloys. TCFE5 and NI-DATA equilibrium databases were used for X65 Steel and Inconel 625, respectively. Module Poly-3 and DEFINE_MATERIAL command of TCC were also used.

2.3. Kinetic simulation

Kinetic simulations of diffusion phenomena occurring throughout the interface between the X65 Steel and Inconel 625, allow obtaining chemical profiles for Fe, Ni, C, Cr and Mo. Calculations were developed using DICTRA module [14]. Geometrical models were employed as depicted in Fig. 2, where X_T is cell width, X_i