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Characterization of the cold ductility degradation after aging in centrifugally cast 20Cr32Ni+Nb alloy tube

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The mechanical properties (yield stress, ultimate tensile stress and elongation) of alloy 20Cr32Ni + Nb subject to isochronal aging at temperatures between 670 and 820 °C for 200 h were investigated using samples extracted from a centrifugally cast tube. The results confirm the occurrence of embrittlement in the aged samples, with maximum embrittlement observed around 770 °C without significant gain in strength.

1. Introduction

Petrochemical furnaces play an important role in the oil industry. In these furnaces the relevant chemical reactions take place between the hydrocarbon molecules (e.g. pyrolysis or reforming) in order to obtain products, like fertilizers, polymers, or raw materials for the pharmaceutical and food industries. Due to the inherent endothermic character of these reactions these furnaces must work at high temperatures (typically up to 1100 °C) and due to productivity reasons they have to remain in continuous service, typically over 100,000 h [1]. The primary attributes of the alloys used in these applications are, therefore, creep strength and corrosion resistance. Secondary aspects of the exposure to high temperatures for long times, however, may manifest in service. This is the case of heat resisting alloys working in the outlet collectors of reformer furnaces, which usually work at temperatures between 700 and 800 °C. A significant degradation of room temperature ductility (characterized by a large loss of elongation in tensile tests) is observed for these alloys and this leads to accidents during maintenance operations (like welding or machining of the parts) [1,2]. This usually leads to total scrapping of the parts, with significant increase in maintenance costs.

To minimize or prevent this ductility degradation of the parts in service, project designers usually specify an aging resistance test, consisting on aging tensile samples taken from the centrifugally cast tubes at 750 °C for 200 h, followed by a room temperature tensile test [3]. To pass this test, the sample must attend minimum ductility requirements (15% elongation) for acceptance of the batch of tubes by the user [3]. This empirical test could be questioned regarding the ability of this aging treatment to detect the ductility degradation, by asking if either the treatment time or the treatment temperature is sufficient to detect the maximum ductility degradation. The aim of the present work is to answer these questions, by testing tensile samples aged for 200 h in temperatures between 670 and 820 °C taken from a centrifugally cast tube made of alloy 20Cr32Ni + Nb (ASTM A351 Grade CT15C).

2. Experimental

2.1. Material

A tube with dimensions outer diameter 247 mm, inner diameter 187 mm and 2000 mm length was centrifugally cast using alloy 20Cr32Ni + Nb (ASTM A351 CT15C). The analyzed average composition[1] of the cast tube was 0.12% C, 0.85% Si, 1.08% Mn, 0.017% P, 0.007% S, 19.8% Cr, 31.9% Ni, 0.01% Mo, 0.02% Co, 0.98% Nb, 0.02% Cu and 0.056% N. All other impurities had contents under 0.01%. This composition agrees with the standard composition range for the alloy. Fig. 1 shows the cast tube. As the centrifugal casting process typically results in a small, but significant, composition gradient along the length of the tube, this was cut in

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[1] All compositions are given in weight %.

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Fig. 1. The centrifugally cast tube investigated in the present work. The tube was cut into four rings (ring number 1 is located in the cold end of the centrifugal casting mold). Rings 1– 3 were reserved for the investigation. The last ring (marked as "Sobra" in the picture) was excluded from the investigation.

three rings, labeled 1–3 (as shown in Fig. 1). A fourth ring, the one located closer to the feeding channel, was excluded from the investigation since it presumably has the highest impurity content in the tube. To warrant the reproducibility of the results, all samples were taken from ring no. 1 when possible. One set of samples, however, was acquired for ring no. 2 and this has an impact on the results (see below).

2.1.1. Microstructure

The microstructure of the samples was analyzed in a scanning electron microscope (SEM), equipped with EDS accessory. The "as cast" microstructure consists of an austenitic matrix with dendritic morphology containing interdendritic primary discontinuous NbC particles. After aging a significant amount of secondary carbides precipitates in the austenitic matrix [4,5]. These particles were identified as chromium carbides (presumably $M_{23}C_6$) via EDS measurements [5]. The nickel–niobium silicide known as "G-phase", which forms out of the NbC particles after aging for alloys of similar compositions [4,6,7] could not be identified in the samples and heat treatment conditions investigated herein.

2.2. Sample extraction

The macrostructure of centrifugally cast tubes of heat resistant alloys is heterogeneous [8], containing a columnar region close to the outer diameter and becoming equiaxial towards the center of the tube. This heterogeneous macrostructure, however, is reproducible along the length and shows approximate radial symmetry around the tube axis. To improve the reproducibility of the test, therefore, the tensile samples must be extracted from the same position relative to the outer diameter. Tensile samples of diameter 8.75 mm and 35 mm gauge length were machined according to the specifications of the ASTM A370-07b (Specimen type 1) Standard. The samples were extracted such that their centers are located 11.75 mm from the outer skin (i.e. the reduced section of the sample was at least 3 mm far from the outer skin) and their length was parallel to the tube axis. Three samples were used for each heat treatment condition. Fig. 2 shows one set of machined tensile samples, including a sector of the original tube for comparison.

2.3. Aging treatments

The set of three samples (including a 2 mm machining allowance in each sample) were radially placed inside a tubular furnace

Fig. 2. One set of machined tensile samples, including a sector (left) of the original tube.

to allow the long-term aging heat treatments in a reproducible manner. Previously calibrated type K thermocouples were attached to each sample to assure temperature homogeneity during the whole treatment. The temperature was controlled within ±5 °C accuracy and the total treatment time was set to 200 h. Four temperatures were selected for the preliminary investigation: 670 °C, 720 °C, 770 °C and 820 °C. Later it was decided to add a set of samples corresponding to $T = 750$ °C to complete the data. This set of samples was extracted from ring number 2, contrary to the original samples, which were extracted from ring number 1 (Fig. 1). The heat treatments were conducted without protective atmosphere, but the adopted machining allowance was found to be sufficient to eliminate any oxided or decarburized layers in the sample's surface.

2.4. Tensile tests

After the heat treatment and machining to final dimensions the samples were submitted to liquid penetrant inspection to detect possible surface flaws in the reduced section. The samples were then tensile tested in a hydraulic testing machine under load increment control. The load increment rate was selected to be 9.8 MPa s^{-1}. Yield, σ_y, and Ultimate Tensile Stress, UTS, were graphically determined following the procedures described in the ASTM A370-07b Standard. Fracture elongation, ε_f, was determined according to the same Standard, by carefully joining the two broken pieces and measuring the change of length compared with the gauge length.

3. Results

3.1. "As cast" state

Tensile testing of the three samples in the "as cast" state resulted in average values of $\sigma_y = 196.7$ MPa (individual values: 194, 197, 199 MPa), UTS = 523.3 MPa (individual values: 520, 525, 525 MPa) and $\varepsilon_f = 41.3\%$ (individual values: 38%, 41%, 45%). An estimate of the ductility through the reduction in area was not attempted due to the irregular aspect of the sample's cross section after deformation, which results from the anisotropy of the deformation due to the large dendritic grain sizes. Fig. 3 shows the surface of one of the "as cast" samples after the tensile testing.

3.2. Aged state

Fig. 4 shows the variation of σ_y, UTS and ε_f for the aged samples, as a function of the aging temperature. The individual measurements are shown as points in the figure. The curves are tendency lines calculated using least-squares regression. A parabolic model (i.e. $Y = a \times T^2 + m \times T + b$, where Y is the property to be modeled)