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High temperature mechanical behavior of tube stackings – Part I: Microstructural and mechanical characterization of Inconel® 600 constitutive material

V. Marcadon [a,*], C. Davoine [a], D. Lévêque [a], A. Rafray [a], F. Popoff [a], N. Horezan [a], D. Boivin [a]

[a] Onera – The French Aerospace Lab, F-92322 Châtillon, France

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ABSTRACT

This paper is the first part of a set of two papers dedicated to the mechanical behavior of cellular materials at high temperatures. For that purpose, cellular materials made of brazed tube stacking cores have been considered here. This paper addresses the characterization of the elasto-viscoplastic properties of the constitutive material of the tubes, Inconel®600, by means of tensile tests. Various temperatures and strain rates were investigated, from room temperature to 800 °C, in order to study the influence of both the brazing heat treatment and the test temperature on the mechanical properties of Inconel®600. Whereas the heat treatment drastically decreases the strength of the tubes, a significant viscous effect is revealed at 800 °C. Electron backscattered diffraction analyses carried out *post-mortem* on samples showed that both dynamic recrystallization and recovery occurred during tensile tests performed at 800 °C, especially at lower strain rates. In contrast, a highly deformed and textured microstructure was observed for the tubes loaded at lower temperatures.

1. Introduction

Metallic cellular structures, such as metal foams, honeycombs, truss lattices, and hollow-sphere or tube stackings, for instance, have been abundantly studied for several years because of their potential for the development of new multi-functional and lightweight structures [1,2]. In order to address this issue, tube stackings have been considered here as a 'model' cellular structure. Indeed, the case of tube stackings is particular, since it is a quite new cellular architecture that has been barely studied, despite presenting an extruded character that is very convenient to develop 2D modeling. Moreover, the elementary tubes can be bought easily and both their geometrical and mechanical properties are very reproducible. Thus, regular stackings can be manufactured with only few defects, which enables a very rich dialogue between experiment and modeling involving large deformations and contact issues. The main mechanism that governs the mechanical behavior of tube stackings is the localized plasticity in the walls of the constitutive cells [3,4]. Therefore, this is significantly different from the case of honeycombs loaded transversally, for which buckling and cell wall instabilities are observed [5,6]. It is mainly a question of ratio between the cell wall thickness and the cell diameter. The reader can refer to the companion paper of this one (see Part II [7]) for a more complete review on the mechanical behavior of cellular structures. Here, focus is on both the mechanical and microstructural properties of Inconel®600 as constitutive material of the tube stacking structure studied.

Inconel®600 is a commercially available Ni-Cr-Fe alloy that exhibits a good combination of strength, formability and environmental resistance at high temperatures. This combination of properties makes this material ideally suited for structural components in chemical processing equipment, nuclear reactors or aerospace applications, for instance. In order to provide a good understanding of the stress corrosion cracking resistance of Inconel®600, microstructural changes that occur when this alloy is heat-treated in the temperature range of 600 °C to 900 °C have been widely studied [8,9]. Bruemmer et al. [10] suggested that the distribution of the grain boundary carbides may induce a mechanical effect, since carbides reduce the crack tip stress state by crack tip blunting. The effect of heat treatments on the mechanical properties of Inconel®600 has been studied also, in particular the role of the carbides located at grain boundaries [11]. Extensive grain boundary cracks are observed on the fracture surfaces of tensile and impact specimens with continuous grain boundary carbides, decreasing the area reduction observed at the rupture. The shortest delay time for precipitation is observed between 800 °C and 900 °C. At higher temperatures, grain growth occurs when the alloy is heated to about 980 °C. At this temperature, the

* Correspondence to: Metallic Materials and Structures Department, France.
E-mail address: Vincent.Marcadon@onera.fr (V. Marcadon).

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carbide particles finely dispersed into the microstructure, which inhibit grain growth, begin to coalesce. Carbide solution begins at about 1040 °C, whereas solution annealing, observed above 1190 °C, results in the dissolution of all of the carbides [12], hence an increased grain size. Moreover, it has been shown that the mechanical properties of Inconel®600 are also affected by the amount of carbon in solid solution [13]. Although most of the carbon resides in carbides, and only a small fraction exists as interstitial solution because of the high chromium content (about 16 wt%) in Inconel®600, the interaction of carbon with mobile dislocations results in dynamic strain ageing. In order to have a better understanding of the mechanisms involved in ultra-fine grain processing techniques, grain boundary engineering, or welding, the effects of both the deformation level and temperature on the microstructure of Inconel® 600 have been investigated recently [14]. Depending on the deformation level and the temperature, various mechanisms, such as static and dynamic recrystallizations or dynamic recovery, may dominate and affect the development of microstructures. In particular, these mechanisms contribute to reducing the strain hardening during the deformation. Dynamic recrystallization was also observed in Inconel®600 friction stir welded samples [15]. Blaizot et al. [16] recently proposed a model accounting for such complex interactions, but for Inconel®690. They showed that, for this alloy, the dislocation density is the main microstructural parameter governing the mechanical behavior for the experimental conditions that they considered.

This work is aimed at studying the elasto-viscoplastic properties of Inconel®600, in order to be able to propose a rich dialogue between experiment and modeling when further characterizing the mechanical behavior of tube stacking structures at high temperatures (see Part II [7]). Although this characterization is presented in Part II only, Section 2 describes the tube stacking studied and its process route to precise the brazing heat treatment applied to the constitutive material. Then Section 3 addresses the characterization of the elasto-viscoplastic properties of Inconel® 600, as constitutive material of the tubes, by means of tensile tests performed on single tubes at different strain rates. Various temperatures were investigated, from room temperature to 800 °C in order to study the influence of both the brazing heat treatment and the test temperature. In order to investigate microstructural evolutions induced by both the heat treatment and the test conditions, electron backscattered diffraction (EBSD) analyses were carried out *post-mortem* on the samples. They are described in Section 4 in terms of deformation mechanisms, twinning and microstructural changes in the grains.

Table 1
Chemical composition of Inconel®600.

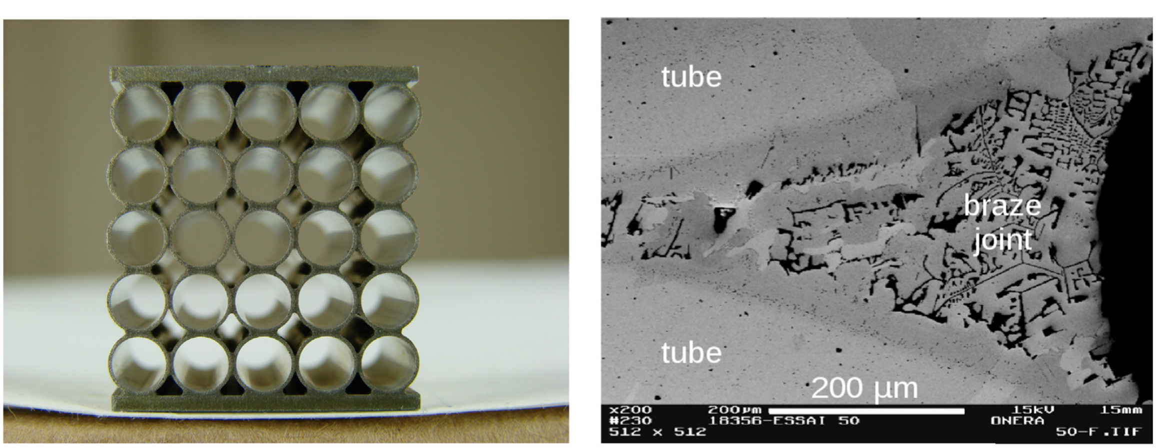
Element	Cr	Fe	Si	Mn	C	Cu	S	Ni
wt% (weight content)	15.5	8.0	0.5	1.0	0.15	0.5	0.01	bal.

2. Studied material

The method for fabricating a 'model' cellular structure consisting of regularly stacked circular tubes is briefly reported here. The small sandwich structure was processed by using a brazing heat treatment. It consisted of two Inconel®600 skins with a thickness of 1 mm and a 5 × 5-tube stacking core. The tubes were made of Inconel®600 also, and their outer diameter and thickness were equal to 4 mm and 250 μm, respectively. These seamless tubes were manufactured by Alloyshop using extrusion and their chemical composition is given in Table 1. This nickel-chromium-iron alloy is a standard engineering material for applications that require resistance to corrosion at high temperatures.

The tubes were bonded to each other and to the skins by using Ni-1.5B-19.0Cr-7.3Si-0.08C (wt%) braze foils. They were stacked in a graphite die lined with Inconel®600 skins, positioned at the top and at the bottom of the stacking in order to provide the sandwich structures. The internal faces of the graphite die were coated with a boron nitride layer to avoid the chemical interactions between carbon and the metallic structure. The main advantage of this braze ensues from its good oxidation resistance properties, compared to those of the Ni-11.0P wt% braze that we have used previously for room temperature applications, for instance [3,4]. A stacking following a square pattern in its transversal plane was produced by this technique (Fig. 1(a)), since this particular braze was available under the shape of 50 μm thickness foils only. The 'square stacking' was achieved by alternatively stacking a layer of tubes and three braze foils. The bonding was achieved by applying a heat treatment in a vacuum furnace. The Ni-1.5B-19.0Cr-7.3Si-0.08C wt% alloy is liquid above 1150 °C. Thus, the heat treatment chosen here consisted in an increase in the temperature at 100 °C min^{-1} up to 1170 °C, then followed by a dwell of 15 min at 1170 °C and, finally, followed by the natural cooling of the furnace. At 1170 °C the liquid concentrated at the contact lines by capillarity, hence metallurgical joints were created between the tubes after cooling.

Energy dispersive spectroscopy (EDS) analyses showed that the braze joint consisted of three distinct phases, brittle intermetallic chromium borides and nickel silicides in a ductile Ni-rich solid



(a) (b)

Fig. 1. (a) Tube stacking performed (b) EDS image of a braze joint between two neighboring tubes (chromium borides are in black, nickel silicides are in light grey and the Ni-rich solid solution is in medium grey).