Cellular materials made of stacked tubes : influence of the manufacturing process on the dynamic behaviour of the constitutive material Part II : mechanical behaviour

G. Portemont, C. Davoine, B. Langrand, V. Marcadon

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retour sur innovation

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Part II : mechanical behaviour.

Matériaux cellulaire par empilement de tubes: influence du procédé de fabrication sur le comportement dynamique du matériau constitutif. Partie II : comportement mécanique.

par

G. Portemont, C. Davoine, B. Langrand, V. Marcadon

Résumé traduit :

L'objet de ces travaux vise à étudier les liens existants entre procédé de fabrication des matériaux cellulaires architecturés et les propriétés mécaniques des matériaux constitutifs. Ce travail préliminaire à la caractérisation d'empilements de tube intéresse plus particulièrement l'évolution de la microstructure et des propriétés mécaniques de l'inconel 600 suite au traitement thermique du brasage et la diffusion de l'alliage de Nickel-Phosphore utilisé pour la brasure. Ces matériaux, l'Inconel 600 et l'alliage de Nickel-Phosphore, sont en effet considérés dans ces travaux pour des applications aéronautiques liées à la résistance à l'impact. Cette communication intéresse plus particulièrement la caractérisation expérimentale des propriétés mécaniques aux chargements dynamiques. Différentes configurations de matériaux sont caractérisées et comparées, incluant à la fois des essais de traction à des vitesses de déplacement quasi-statique et dynamique. Les résultats montrent que le comportement de l'inconel 600 utilisé pour les tubes est viscoplastique avant traitement. Toutefois, le traitement thermique agit tel un traitement de recuit qui restaure les propriétés plastiques de matériau des tubes et élimine les effets viscoplastiques. Des analyses d'EBSD réalisés sur les éprouvettes de traction montrent une forte texture, résultant du chargement de traction. Une orientation intragranulaire homogène est aussi observée dans les grains, reflétant de grande déformation plastique. Ces analyses EBSD sont présentées plus en détails dans une communication par Davoine et al. Les paramètres d'un modèle de Johnson et Cook sont identifiés pour chaque configuration de matériaux. Ces modèles seront utilisés dans la suite des travaux dont l'objet vise la caractérisation expérimentale et numérique du comportement mécanique des empilements de tubes.

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Cellular materials made of stacked tubes:
influence of the manufacturing process on the dynamic behaviour of the constitutive material
Part II: mechanical behaviour

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Abstract
The purpose of these works is studied the link that exists between the manufacturing process of cellular architectures and the mechanical properties of their constitutive materials. It is a preliminary work to the mechanical characterisation of regular tube stackings which focuses on the evolutions of both microstructures and mechanical properties of Inconel 600 resulting from brazing heat treatment and diffusion of the brazing compounds. Reference is made to Inconel 600 tube stacking brazed using a nickel-phosphorus alloy in view of aeronautical applications, for instance impact resistance. The paper interests more precisely the experimental characterisation of the mechanical properties faces to dynamic loads. Different material configurations are thus characterised and compared, involving both tensile tests from quasi-static to dynamic. Results show that a viscous effect on the mechanical behaviour of Inconel 600 exists in the tubes before heat treatment. However, the heat treatment acts such as a recovery treatment on the plastic properties of the tube material eliminating viscous effects. Electron back-scattered diffraction (EBSD) post-mortem analyses of the tensile specimens show a strong texture too, resulting from the tensile loading and a quite homogeneous intragranular misorientation is observed inside the grains, reflecting large plastic deformations. EBSD analyses are presented in more details in a paper by Davoine et al. Different mechanical properties have also been identified according to Johnson-Cook's model. They will be used in future works addressing the experimental characterisation and the finite-element modelling of the mechanical behaviour of tube stackings.

1. Introduction

Cellular materials are very promising as lightweight aeronautical frames thanks to their superior specific mechanical properties such as impact resistance [1]. However, because of the processing routes and heat treatments used in the production process, the material within the cell walls may behave differently from the bulk, and therefore the *in situ* mechanical properties are often unknown [2,3]. The present works aims at investigating the link that exists between the processing of cellular architectures and the mechanical properties of their constitutive material. The cellular material studied is an Inconel 600® tube stacking brazed using a nickel-phosphorus alloy (Figure 1).

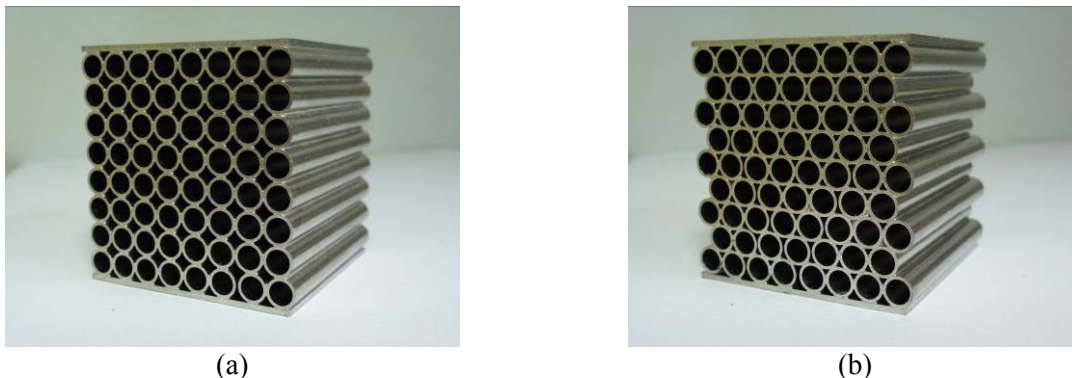(a)   (b)
Figure 1: Cellular structures considered: (a) square stacking core, (b) hexagonal stacking core.

The experimental works have been performed in order to analyse the mechanical characterisation of regular tube stackings that focuses on the evolutions of both microstructures and mechanical properties of Inconel 600® resulting from brazing heat treatment and diffusion of the brazing compounds [4]. The confrontation of the mechanical properties and microstructures using electron back-scattered diffraction analyses (EBSD) are presented in more in a paper by Davoine et al. [5]. Different material configurations are thus characterised and compared, involving both tensile tests from quasi-static to dynamic loads and. In order to discuss the influence of the manufacturing process of tube stackings on the mechanical properties of their constitutive material, it has been proposed to perform uni-axial tensile tests at various strain rates on tubular specimens for three different materials configurations. The first one was made of base metal material (Inco600BM), the second one was affected by the brazing heat treatment (Inco600HT), and the latest was submitted to the NiP layer deposition then followed by the brazing heat treatment (Inco600NiP).

2. Experimental device for the material behaviour characterisation under high strain rate

2.1 Experimental set-up

In order to discuss the influence of the manufacturing process of tube stackings on the mechanical properties of their constitutive material an Inconel 600® here, it has been proposed to perform uni-axial tensile tests at various strain rates on tubular specimens for the three different material configurations. The cellular materials in Figure 1 being possibly subjected to dynamic loads (i.e. fan blade off application for instance), the mechanical behaviour of the three tube material configurations has also been studied under different strain rates in order to analyse possible viscous effects.

The strain rate dependency of the three various Inconel600® configurations was studied with a uni-axial tensile device developed for tubular specimens. The device in Figure 2 makes it possible to clamp the tubular specimen all around its section. A rigid pin was inserted into the tubular specimen in each gripping area (upper and lower holders) of the specimen in order to avoid its deformation during the tightening before testing. This specific device has been developed especially for high strain rate testing by using a hydraulic jack. Each specimen was subjected to a uni-axial tensile loading at a given strain rate, by using a hydraulic jack and the experimental device (Fig. 2).

Force, displacements and strains were measured the same way for the tests performed in quasi-static and dynamic loading conditions. The force was measured by a piezo-electric load cell and the elongation was measured by an optical extensometer and the black/white mark on one side of the specimen (Fig. 3). A strain gauge was bonded on the other side of each specimen as presented in Figure 3. Tests were performed at various imposed velocity varying between 6mm.min^{-1} (1.10^{-3}s^{-1}) and 2m.s^{-1} (100s^{-1}). The actual strain rates were analysed for each test using the strain measurement given by the strain gauge. For each material configuration, a set of three tests to the minimum was performed at the same displacement rate to assess the experimental or material discrepancy.
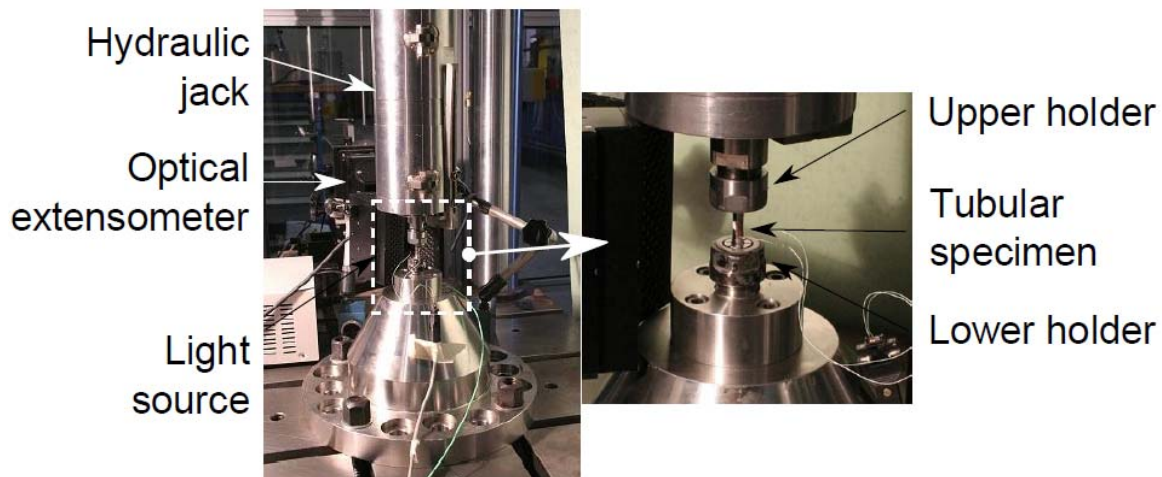

Figure 2: Experimental set-up for the tensile tests at high strain rates on tubular specimens

2.2   Design of the tubular specimen

Using smooth specimens, plastic strain developed near the gripping areas for very low levels of average strain. The analysis of the material behaviour was consequently limited to engineering strain levels lower than 5% using the smooth tubular specimen. The machined tubular specimen shown in Figure 3 has been especially developed to avoid plastic strain localisation and failure near the gripping areas and to make the analysis of the tube material behaviour possible under a wide range of average strains and strain rates.

Tubular samples were machined from 75mm length tubes with external and internal diameters equals to 6mm and 4mm respectively. The tubes were originally produced using extrusion and cold drawing. The external diameter in the centre of the specimen corresponds to the external diameter of the tubes implemented in the cellular materials in Figure 3, i.e. 5mm. This is particularly important that the tubular specimens for tensile testing and the tubes within the cellular materials have a similar diffusion and penetration of the brazing metal (i.e. the NiP alloy) into the Inconel 600® base material. Hence the set of Inco600NiP specimens has been coated by a 15μm thickness NiP layer. This thickness has been calibrated in order to produce a similar diffusion and penetration of the brazing metal into the base metal, compared to the actual manufacturing process.
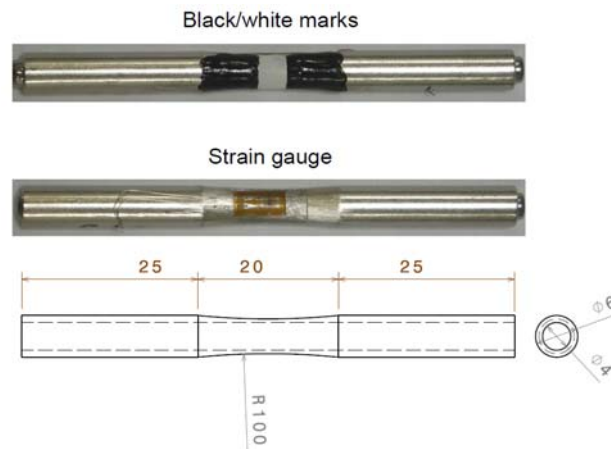

Figure 3: Tubular specimen for tensile testing. The strain was measured on one side of the specimen by an optical extensometer with black and white marks, and on the other side by a strain gauge.

Preliminary tests have been performed with a stereo digital image correlation (DIC) system to attest the strains uniformity over the gauge length of the machined tubular specimen (Fig. 4). These tests results were compared with the others tests performed on the smooth tubular specimens with external and internal diameters that equalled to 5mm and 4mm respectively. The stress *versus* strain response obtained for both specimens (smooth and machined specimens) was very close until the plastic localisation in the smooth specimen.
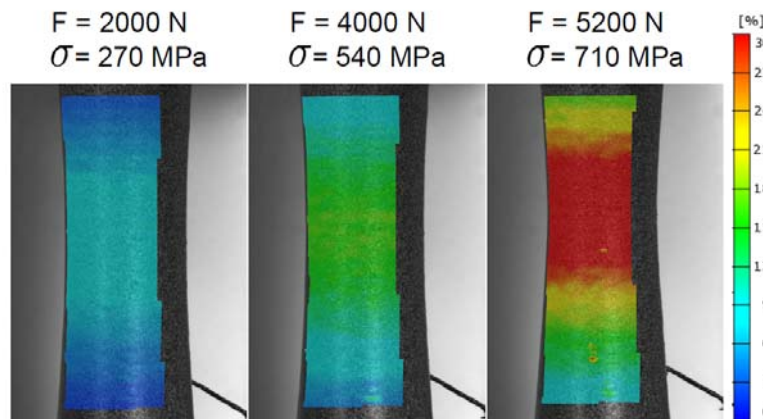

Figure 4: Tensile strain distribution measured by stereo Digital Image Correlation for different uni-axial tensile stresses (machined tubular specimen)

3. Experimental results

The strains measured by both the strain gauge and the optical extensometer delivered the same measurements until the failure of the strain gauge. The stress time history shows high frequency oscillations for the tests performed at a displacement rate of 1m.s^{-1}. These oscillations came from the first natural frequency of the experimental device (i.e., lower holder in Figure 2) that disturbed the measurements of the load cell during the dynamic test. Performing tests at displacement rates higher than 1m.s^{-1} would have increased the amplitude of these oscillations and digital filtering would have been necessary to analyse the results. That is reason why the dynamic tests were limited to displacement rates of 1m.s^{-1} in our study. Experimental results presented in the paper are consequently raw data. These measurements are analysed to define the engineering stress *versus* engineering strain diagrams obtained at different strain rates.

Experimental results show similar standard deviations whatever the displacement rate applied to the specimen, except for the tests performed at 0.2m.s^{-1}. This can be explained by the fact that the hydraulic jack used to perform the tests could not maintain a constant strain rate at this specific displacement rate. However, the standard deviation is about 7% and remains acceptable for dynamic tests.

3.1 Inco600BM: as-received tube material

The material properties evolve on the strain rate. Lee et al. [6] and Wang et al. [7] have already observed strain rate dependency for other Inconel® materials. Whereas Young's modulus, E is not dependent on the strain, both the yield and ultimate stresses, σ_y and σ_u, increase significantly and gradually with the strain rate. Results show that the material behaviour of the Inco600BM base material is elasto-visco-plastic. The rate effect appears from the tests performed at 0.7s^{-1}. Complementary tensile tests have been performed at displacement rates varying between 1.10^{-4}m.s^{-1} and 8.10^{-3}m.s^{-1} in order to better estimate the strain rate threshold above which a viscous effect appears. Results were not influenced by the strain rate until values close to 0.28s^{-1}.

The engineering stress *versus* engineering strain diagrams obtained at different strain rates are presented in Figure 5 (featuring the test at 0.28s^{-1}). The engineering strain is those delivered by the strain gauge until the failure of the sensor. These diagrams will be used in the following section to analyse the true stress *versus* true plastic strain relationship observed at different strain rates and then identify the parameters of a constitutive material law.
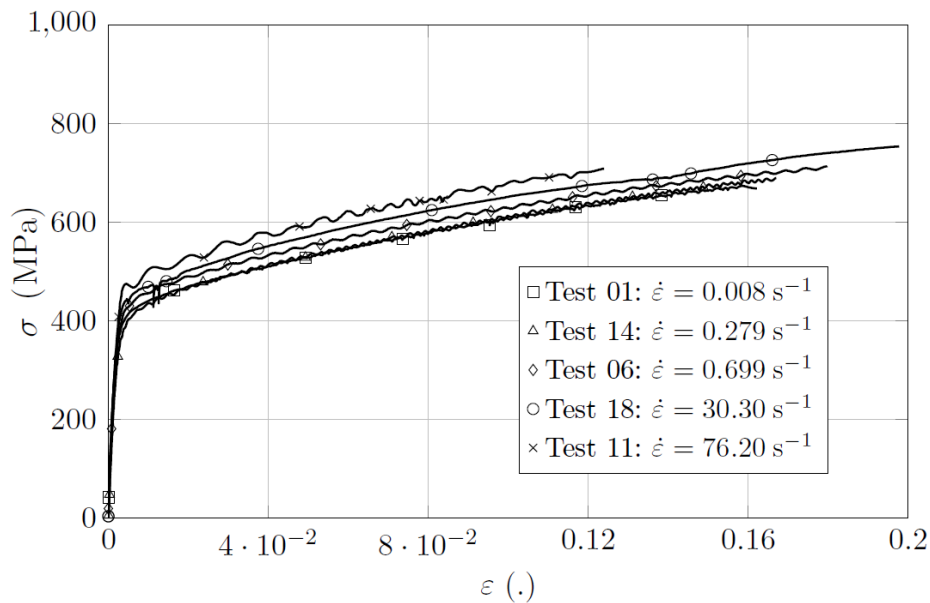

Figure 5: Engineering stress vs. strain diagram for the Inco600BM material. The engineering strain is given by the strain gauges

3.2 Inco600HT: tube material affected by the heat treatment

This section deals with the experimental characterisation of Inconel®600 that has been subjected to the heat treatment only before tensile testing. The heat treatment was applied once the specimens were machined. The observation of the specimen shows no permanent deformation after the heat treatment. The tubular specimens were tested at various displacement rates using the same aforementioned experimental protocol. The standard deviation increases a little in dynamic loading conditions, but experimental results remain satisfactory (e.g. 2.4% for the yield stress in static loading conditions and 7.6% at a displacement rate of 1 m.s^{-1}). They do not highlight strain rate effects on the yield and ultimate stresses when Inconel ®600 is subjected to the heat treatment only. The engineering stress versus engineering strain diagrams obtained for the Inco600HT material at different strain rates are presented in Figure 6. Once again, the engineering strain is that delivered by the strain gauge until the failure of the sensor.
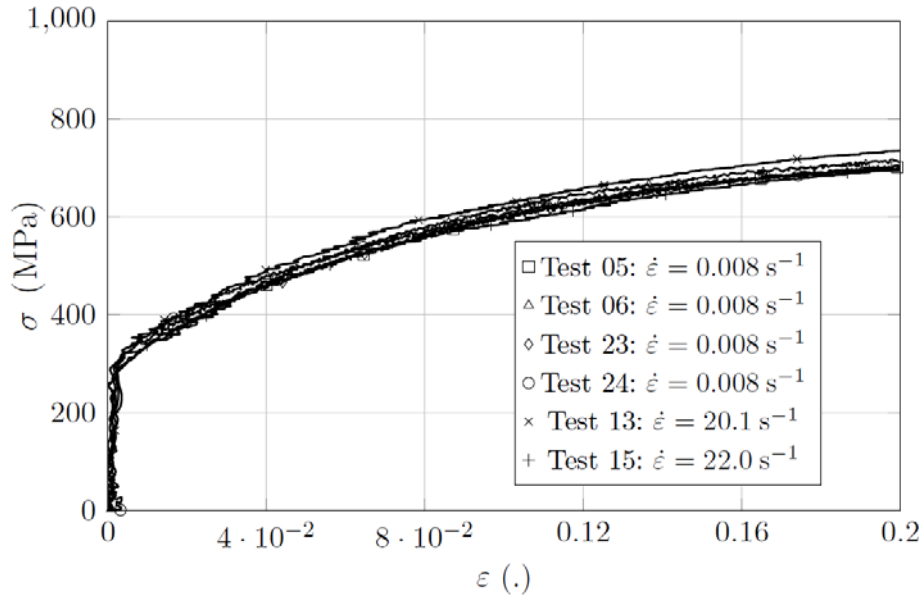

Figure 6: Engineering stress vs. strain diagram for the Inco600HT material. The engineering strain is given by the strain gauges

3.3 Inco600NiP: tube material after the NiP layer deposition and the heat treatment

This section addresses the experimental characterisation of the Inconel R 600 material that was covered with a NiP layer and then subjected to the heat treatment before tensile testing. The heat treatment was exactly the same as the one already described in Section 2.2. The tubular specimens were tested by using the same experimental protocol, as previously. For this set of experiments, the strain gauges debonded for very small strain level ($< 3\%$) even when using epoxy adhesives, such M-Bond AE-10 by Vishay, and cure cycles for polymerisation. The NiP layer turned to be brittle making failure of the strain gauges too. Consequently, it has been decided to consider only the optical extensometer for the strain measurement.

Results exhibit a larger discrepancy for this particular material configuration. It can be explained by the presence of the 50μm thickness NiP layer which was applied to the external and internal surfaces of the tube. When the heat treatment was operated, the final thickness of the NiP layer over the specimen gauge length could not be totally controlled. If the external diameter could be measured in the gauge length of the specimen, the actual internal diameter could not, making uncertainties regarding the cross section of the specimen. Consequently, material behaviour differences observed at the different strain rates could come from differences between the actual section of each specimen and its estimate using the only external diameter. Other tensile tests have been performed at higher strain rates and the results observed at 200s^{-1} remain similar to those obtained at 20s^{-1} as shown in Figure 7. If the material behaviour is affected by the strain rate, the rate effect is below the experimental discrepancy.
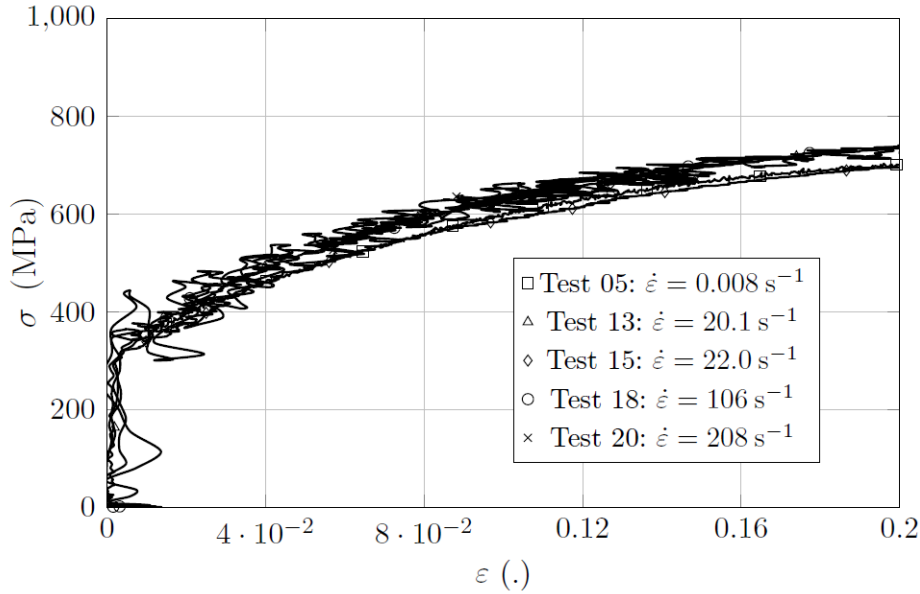
Figure 7: Engineering stress vs. strain diagram for the Inco600NiP material. The engineering strain is given by the strain gauges

3.4 Discussion

The tensile behaviours observed under quasi-static loading are compared for the three material configurations considered. The engineering strain given by the optical extensometer is used to compare the mechanical responses until failure (Figure 8). Whereas the heat treatment significantly decreases the initial yield stress of the base material, the diffusion and the penetration of phosphorus into the tube material does not increase the initial yield stress of the metal. Yield stresses measured for both Inco600HT and Inco600NiP materials are very similar. However, the diffusion and the penetration of phosphorus results in an increase of the material hardening.
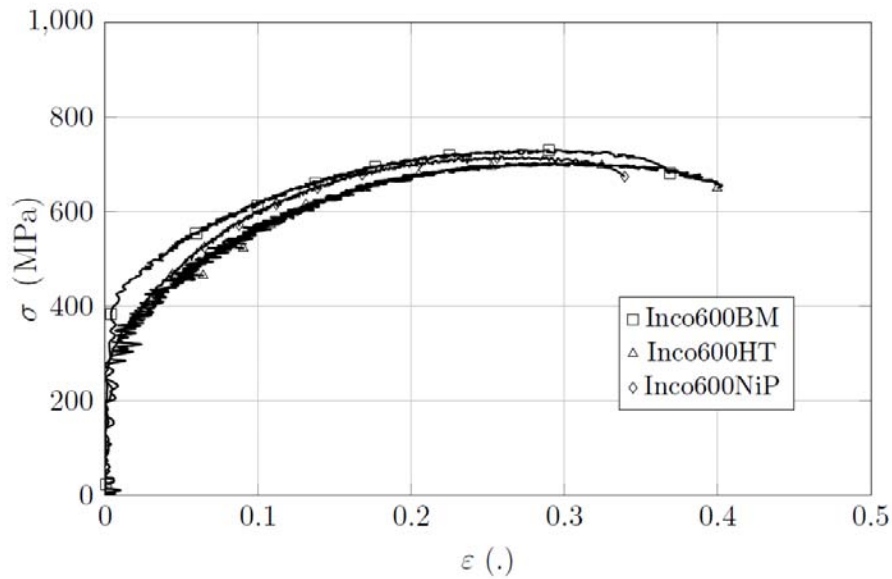

Figure 8: Engineering stress vs. strain diagram for the three material configurations tested for 1.10^{-3} s^{-1}

Inco600BM tubes were obtained by cold stretching that induced plastic strain and increased the material yield stress. Thus the heat treatment acts such as a recovery of the microstructure and the mechanical properties of the tube material after its mechanical processing (e.g., cold drawing). When offsetting the total strain of the Inco600BM material to project the yield stress of the Inco600BM material on the stress versus strain diagram of the Inco600HT material (here a strain offset of about 0.03 is added to the total strain), it is observed that the hardening of both material configurations (Inco600BM and Inco600HT) are very similar up to strain levels close to 0.2.It is worth noting that the

strain to fracture of the Inco600HT material is approximately the same than that of the Inco600BM material with the aforementioned strain offset.

4. Conclusions

The present works aims at investigating the link that exists between the processing of cellular architectures and the mechanical properties of their constitutive material. The cellular material studied is an Inconel 600® tube stacking brazed using a nickel-phosphorus alloy. The experimental works have been conducted in order to analyse the mechanical characterisation of regular tube stackings that focuses on the evolutions of mechanical properties of Inconel 600® resulting from brazing heat treatment and diffusion of the brazing compounds.

Different material configurations are thus characterised and compared, involving both tensile tests from quasi-static to dynamic loads. In order to discuss the influence of the manufacturing process of tube stackings on the mechanical properties of their constitutive material, it has been proposed to perform uni-axial tensile tests at various strain rates on tubular specimens for three different materials configurations. The first material configuration tested is the tube material base metal (Inco600BM), the second material configuration is related to the tube material affected by the brazing heat treatment only (Inco600HT) and the latest material configuration is related to the Inconel 600 tube material submitted to the NiP layer deposition then followed by the brazing heat treatment (Inco600NiP).

A specific device has been developed especially for high strain rate testing by using a hydraulic jack. Results show that a viscous effect on the mechanical behaviour of Inconel 600 exists in the tubes before heat treatment, the material behaviour is elasto-visco-plastic. However, the heat treatment acts such as a recovery treatment on the plastic properties of the tube material that eliminates viscous effects. Different mechanical properties have been identified according to Johnson-Cook's model [8].

Electron back-scattered diffraction (EBSD) post-mortem analyses of the tensile specimens show a strong texture too, resulting from the tensile loading and a quite homogeneous intragranular misorientation is observed inside the grains, reflecting large plastic deformations. EBSD analyses are presented in more details in a paper by Davoine et al. [5].

The experimental investigation has been proposed to characterize of the tube stackings in Figure 1 for the dynamic compressive loading. All experimental results (tensile tests on machined tubular specimen, compressive tests on the tube stackings) will be used in future works addressing the finite-element modelling of the mechanical behaviour of tube stackings.

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