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Experimental and numerical characterization of a mechanical expansion process for thin-walled tubes

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ABSTRACT

Air heat exchangers are made with tubes joined to finned pack. The connection between tubes and fins can be obtained through a mechanical process where an ogive is pushed inside the tube with smaller internal diameter causing its expansion. Residual plastic deformation provides the assembly with the fins. Accurate connection over the whole contact area of the tubes and fins is essential for maximum heat exchange efficiency. The goal of this work is to study and develop a finite element model able to effectively simulate expansion forming, allowing process analysis and, eventually, process optimization. The paper is divided into a first experimental part, where the materials used for the heat exchangers are characterized, and a second numerical part where models have been developed on the basis of the experimental data. The developed models are used to identify the material properties with an inverse method, and then to study the technological process of tube expansion by using a simplified but sufficiently accurate description. The model has proved to be an effective design tool, as it can evaluate the influence of the main parameters on the process and so optimize production according to technological variations.

1. Introduction

In air heat exchangers production, tubes often made of copper and nickel alloys are joined to finned packs. The connection between tubes and fins must provide complete contact in order to ensure maximum heat exchange between the fluids that pass through the parts. The assembly is usually obtained through tube deformation, by means of hydraulic or mechanical expansion processes. In the first case, the manufacturing route uses a fluid medium conveyed inside the tube using high internal pressure. In the second case, an axisymmetric tool whose outer diameter is greater than the internal diameter of the tube is pushed inside the tube. Eventually, the permanent deformation caused by the tube expansion creates the assembly by interference of the tube with the front plates and the fins. For the mechanical process, there are two ways: one use a ball pushed by high pressure water and another use truncated-cone-nose ogive derived by mechanical actuator.

Previous analytical models have been developed by many authors, as summarized by Nadai (1950). In recent years, the analytical model developed by Karrech and Seibi (2010) allows the prediction of the driving force, the dissipated energy and the ogive angle, and it has been validated by finite element analysis. Almeida et al. (2006) refreshed and extended the fundamentals of tube expansion and reduction using a die, by means of comprehensive theoretical and experimental investigation. They defined the formability limits of this process: ductile fracture, local buckling and wrinkling. Tang et al. (2008) proposed a complete study of the expansion process where a thick walled microgroove copper tube is joined to aluminium fins. The results indicate that thermal–mechanical performance is mainly influenced by the expanding ratio. Tang et al. (2009) conducted FEM analysis, supported by experimental investigations, to study the effect of groove shape on forming quality. The outcome shows that the groove height reduction is heavily affected by the helix angle. The same approach was used by Alves et al. (2006) to study the influence of process parameters on the formability limits due to ductile fracture and wrinkling. The influence of expansion parameters on stress levels has been studied by Seibi et al. (2011) for aluminium and steel tubes examining expansion forces and the spring back phenomenon. Tang et al. (2011) have developed an FE model to improve the tube–fin contact of heat exchangers. The FE method has also been used to investigate a real tube sheet fracture, as proposed by Li et al. (2010).

In this context, the aim of this work is to describe a comprehensive step-by-step procedure to analyze the forming process of the expansion, which starts from the material characterization and concludes with a finely tuned simulation of the complete expansion process. The model allows the in depth evaluation of the influence of the main process parameters. As a result, a detailed

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Table 1
FE material model parameters.

Material model parameter	Value
Yield stress σ_0 (MPa)	102
Isotropic hardening parameter Q_{r1} (MPa)	360
Isotropic hardening parameter C_{r1}	9
Cowper and Symonds constant c (s^{-1})	33.8
Cowper and Symonds constant p	1.6

analysis of the expansion phenomenon is shown, which highlights the dependence of most important material and process related parameters.

This paper is divided into a first experimental part, dedicated to the material analysis and to the expansion process study, and a second numerical part, with the development of FE models on the basis of the obtained data.

2. Experiments for material properties and driving force

2.1. Material properties

Different tensile tests were performed in order to study the mechanical properties of the tubes. The tests were carried out in accordance with the ASTM E8M-98 (1998) standard for tube specimen by means of an Instron 8801 testing machine. The tubes were in Cu–Ni alloy, the overall tube length L was 208–210 mm, and the external diameter was fixed to $D_e = 15.85$ mm (non-expanded tube). On the whole, four different types of samples were examined:

- tube thickness values: $t_0 = 1.0$ and $t_0 = 1.5$ mm;
- 2 process grades: non-expanded and expanded.

The tests were performed in stroke control, and conducted to bring the samples up to failure in tension. In order to investigate the strain-rate effect, three loading speeds were examined: $v = 0.1$, $v = 5$ and $v = 100$ mm/s. In accordance to the test standard ASTM E8M-98 (1998), a steel plug was inserted into both ends of the samples to avoid collapse of the section when the tube is laterally compressed by the grips of the testing machine.

The results in terms of stress–strain curves are presented in Fig. 1: the graphs refer to the case $t_0 = 1$ mm. For both the non-expanded and expanded tube conditions, results from loading at the three different speeds are shown. The obtained curves show that the yield stress in the expanded tubes is more than twice the yield stress in the non-expanded tubes. Conversely, non-expanded tubes show a greater amount of strain hardening. The results confirm that the material has moderate strain-rate sensitivity: nevertheless, even if variations are not so significant in the range of strain-rates typical of the studied process, the strain-rate sensitivity was included in the model of the material. In particular the Cowper–Symonds model (constants c and p in Table 1) was used as discussed in Section 3.1.

2.2. Driving force

To acquire reference data for the development of the numerical models, and for the sensitivity analysis, experiments reproducing the production route were performed. Due to the complexity of the equipment used to manufacture the heat exchanger, which did not allow for a direct measurement of the process parameters, a simplified test equipment was designed and used. Two different experimental set of tests were defined: (1) the mechanical expansion of unconstrained (free) tubes, and (2) the mechanical expansion of tubes constrained by a simplified dummy exchanger. As for the previous tests, the wall thickness was $t_0 = 1$ mm and $t_0 = 1.5$ mm, and the insertion speed was $v = 10$ mm/s (for the unconstrained tubes only) and $v = 100$ mm/s. Grease, applied over the ogive surface, was used to insure proper lubrication. Finally, at least three repetitions of each test were performed.

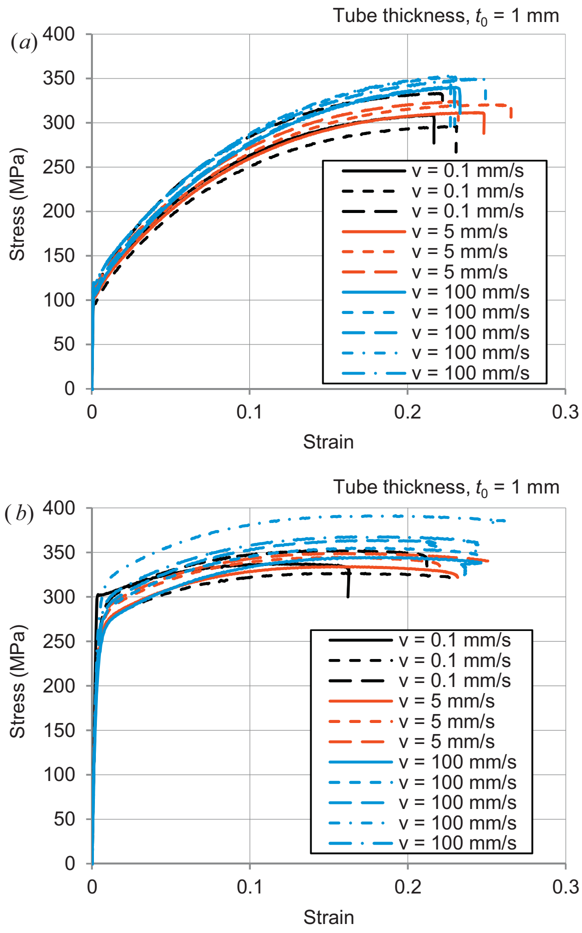

Fig. 1. Stress–strain characteristics for the non-expanded (a) and expanded (b) samples, with thickness $t_0 = 1$ mm.

In the first set of tests, the unconstrained tube was clamped at one end by one of the grips of the testing machine, whereas the ogive was inserted into the other end of the tube, as shown in Fig. 2. However, a pre-forming of the tubes is used in the process. Pre-forming slightly enlarges the first 10 mm in length, leaving a series of wrinkles. These wrinkles, as it will be shown later in Section 3.2, affect the results in terms of the measured insertion force.

In the second set of tests, tubes to be expanded were constrained in the dummy heat exchanger, which is a small assembly reproducing the construction of a typical heat exchanger with six tubes arranged in a hexagonal pattern around the central tube (the tube to be expanded). Normal production plate fins were used to build this assembly, shown in Fig. 3. Again, the central tube was clamped by one grip of the testing machine, and the ogive was inserted in the other end of the tube. This second set of tests was aimed to be more representative of the real production process. These tests were performed at the greater speed of $v = 100$ mm/s only, this speed being close to the expansion speed used in the real production process. The experimental results are presented in Section 3.2, compared with the numerical results.