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Technical Report

# Hybrid friction diffusion bonding of aluminium tube-to-tube-sheet connections in coil-wound heat exchangers

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ABSTRACT

The present study presents and evaluates an application of a new solid-state bonding process, hybrid friction diffusion bonding (HFDB). HFDB is used to fabricate tube-to-tube-sheet connections for aluminium coil-wound heat exchangers. An industry-applicable process variant is developed, and its feasibility is demonstrated by gas leak tightness tests and tensile pull-out tests. The joints meet the requirements of industrial applications. Furthermore, the process is characterised by the thermal field development in the weld area and the applied process forces. The microstructure of the joint is investigated, and dynamic recrystallization is assumed to be the primary grain refinement mechanism in the thermo-mechanically affected zone.



## 1. Introduction

Heat exchangers are commonly used for efficient heat transfer between different media and are widely used in industrial applications, such as petroleum refineries, power plants, and natural gas processing units [1,2]. Coil-wound heat exchangers are typically used to create liquefied natural gas (LNG), as shown in Fig. 1(a). For this low-temperature application, the heat exchangers are typically made from 5xxx series aluminium alloys [1,2]. The fabrication of aluminium coil-wound heat exchangers presents several challenges [3–5], one of which is joining the tubes to the tube sheet, as shown in Fig. 1(b).

Hybrid friction diffusion bonding (HFDB) is a solid-state bonding process that was developed and patented by Helmholtz–Zentrum Geesthacht GmbH (HZG) and first described by Roos [6,7]. HFDB can bond similar and dissimilar materials using a combined friction and diffusion process. This process was originally developed to join thin sheet metals and foils (up to 1 mm in thickness) [6–8]. A friction-based heat input on the surface of the workpieces accompanied by certain deformations activates diffusion processes over the contact surface of the materials to be joined and thus creates a metallic bond [7–11].

HFDB has been selected as a viable alternative to the currently used joining processes due to its robustness and efficiency as a mechanical joining process.

In this work, the new HFDB process is adapted to join tube-to-tube-sheet connections in coil-wound heat exchangers. The dimensions of the tubes and tube sheets are noted in Fig. 2(a). A special tool was designed and manufactured from hot working steel, which is commonly used as tool material in solid-state joining [12]. The tool consists of the friction surface shown in Fig. 2(a1) and a conical feature shown in Fig. 2(a2) to apply friction to the inner side of the tube.

Before the actual joining process, the tube and tube sheet are pressed against each other using a conical tube expander to hold the workpieces in place. The pressing is performed such that an excess tube length of 1 mm is created, which protrudes out over the upper surface of the tube sheet.

The tool is rotated at a speed of $n_T$ in the joining process. A predefined axial force $F_P$ is then applied. Fig. 2(b) and (c) illustrate that the joining process can be divided into two phases. During the insertion phase, only the conical feature is in contact with the inner side of the tube. The applied friction generates heat, and the tube material in the contact zone between the conical feature and tube is plasticised. Furthermore, the oversized conical feature exerts

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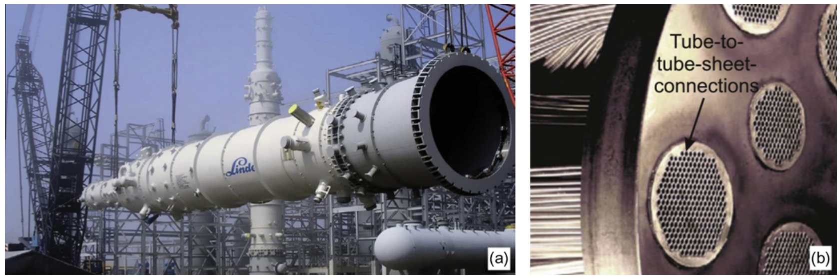


**Fig. 1.** (a) Coil-wound heat exchanger for the liquefaction of natural gas; and (b) tube-to-tube sheet connections on a coil-wound heat exchanger. *Source:* Linde AG.

significant pressure on the contact zone and causes plastic deformation of the workpiece in the weld area. Both the conical feature and friction surface are in contact with the workpiece during the welding phase. Full contact between the tool and workpiece results in a high heat input that, in addition to the applied pressure, joins the tube and tube sheet due to activating diffusion processes in the contact zone between the tube and tube sheet. Finally, the tool is retracted after a predefined welding time.

In this work, tubes and tube sheet dummies were used as workpieces to represent actual tube-to-tube-sheet connections, as shown in Fig. 2(d).

The objective of the joint project between HZG and Linde AG was to investigate the fundamentals and feasibility of HFDB for efficiently joining tubes to tube sheets. The primary demands posed for a tube-to-tube-sheet joint are leak tightness against helium and a tensile strength of 80% or greater of the base material (BM) strength. These demands are to be met through a robust and cost-effective process. This paper investigates the basic process principles, such as the temperature and deformation influence on the bond and the microstructure of the bond.

## 2. Experimental procedures and materials

In accordance with the materials used in coil-wound heat exchangers for cryogenic applications, aluminium alloys solid solution strengthened alloys of the 5xxx series were used for the tube sheet dummies and tubes, respectively [1,3,13]. Table 1 presents the chemical composition of the two alloys [14]. Fig. 3 presents the microstructure of the two materials. The 5xxx series alloy, as used in this work for the tube sheet dummies, is a drawn material with the typical flattened grain structure in the drawing direction. The black indicators in the microstructure represent second-phase particles, identified as intermetallic compounds, such as Mn, Fe, Cr, $Al_6$, $Mg_2Si$, and $Mg_5Al$. These second-phase particles are the nuclei that are essential for recrystallization during hot deformation [15–17]. The 5xxx series alloy used for the tubes presents the typical structure of an annealed aluminium alloy with equiaxed grains [15,18].

All experiments described in this work were performed on a Tricept 805 5-axis parallel kinematic robot in a tripod configuration currently in supply from PKM-Tricept in Pamplona, Spain. The

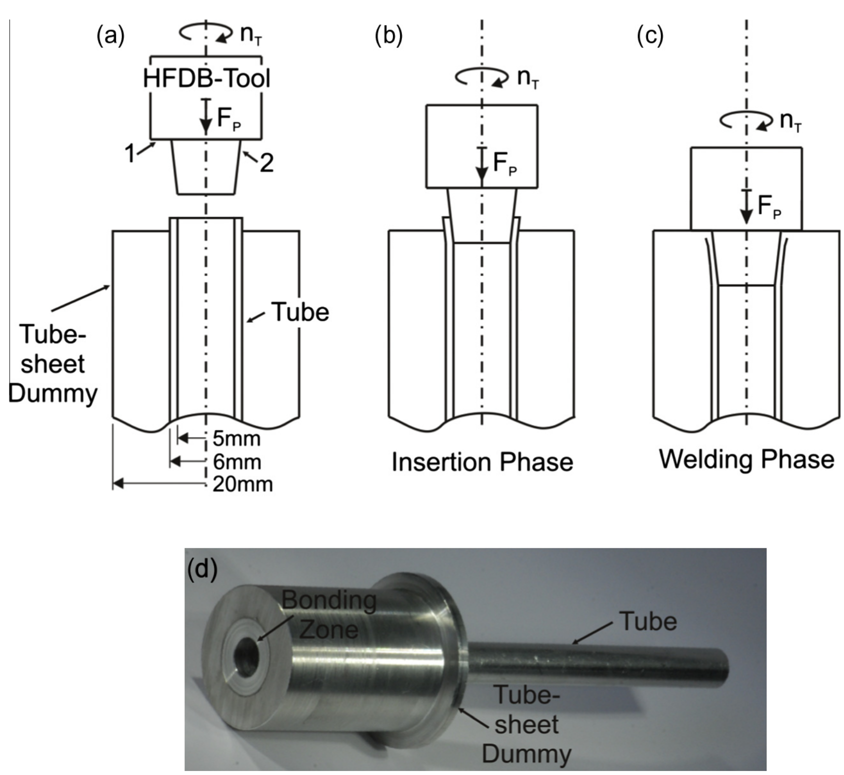


**Fig. 2.** (a) Schematic overview of the HFDB tool and workpieces with (1) a friction surface and (2) a conical part; and HFDB process phases: insertion phase (b) and welding phase (c); and (d) actual bonded specimen with bonding zone (left) of tube-sheet dummy and tube.