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Cascade control of the friction stir welding process to seal canisters for spent nuclear fuel

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ABSTRACT

This article presents the development to reliably seal copper canisters containing the Swedish nuclear waste, using friction stir welding. To avoid defects and welding tool fractures, it is important to control the welding temperature within a span of 790–910 °C. A cascade controller is used to efficiently suppress fast power input disturbances reducing their impact on the temperature. The controller is tuned using a recently presented method for robust PID control. Results show that the controller keeps the temperature within ±10 °C during the 40 min long joint line sequences. Apart from the cascaded control structure, good process knowledge and control strategies adapted to different weld sequences have contributed to the successful results.

1. Introduction

1.1. Background

The Swedish Nuclear Fuel and Waste Management Company (SKB) plans to join at least 12,000 lids and bases to the extruded copper tubes containing Sweden's nuclear waste, using friction stir welding (FSW) as described by Thegerström (2004). The canisters produced (5 m height, 1 m diameter, made out of oxygen-free copper) are a major component of the Swedish system for managing and disposing of radioactive waste. They will be stored in the Swedish bedrock and must remain intact for 100,000 years. A corrosion barrier of 5 cm thick copper and a cast iron insert for mechanical strength are used to meet this requirement. Fig. 1 illustrates the barriers that will jointly prevent the radioactive substances in spent fuel from spreading into the environment.

To ensure that high quality welds are produced repeatedly during more than 40 years of production, there is an evident need for automated welding instead of the past procedure depending on a skilled welding operator. A correctly tuned controller will not only be able to react to process disturbances faster, but also produce a more reliable process throughout the approximately 45 min long weld cycles.

1.2. Friction stir welding

FSW is a thermomechanical solid-state process that was invented in 1991 at The Welding Institute (TWI) in Cambridge, England (Thomas et al., 1992). A rotating non-consumable tool, consisting of a tapered probe and shoulder, is plunged into the weld metal and traversed along the joint line, see Fig. 2. For thick section welds (e.g. the copper canisters), a pilot hole has to be drilled to make the plunge sequence possible without significant probe wear. Frictional heat is generated between the tool and the weld metal, causing the metal to soften, normally without reaching the melting point, and allowing the tool to traverse the joint line. Deeper knowledge of FSW and its applications in industry can be gained from reading e.g. Mishra and Mahoney (2007), Nandan, DebRoy, and Bhadeshia (2008) and Lohwasser and Chen (2009).

2. Process description

2.1. Technical data

In 2003, a purpose-built machine from ESAB was installed at SKB's Canister laboratory in Oskarshamn (see Fig. 3). In this machine, the welding head rotates up to 425° around the canister,

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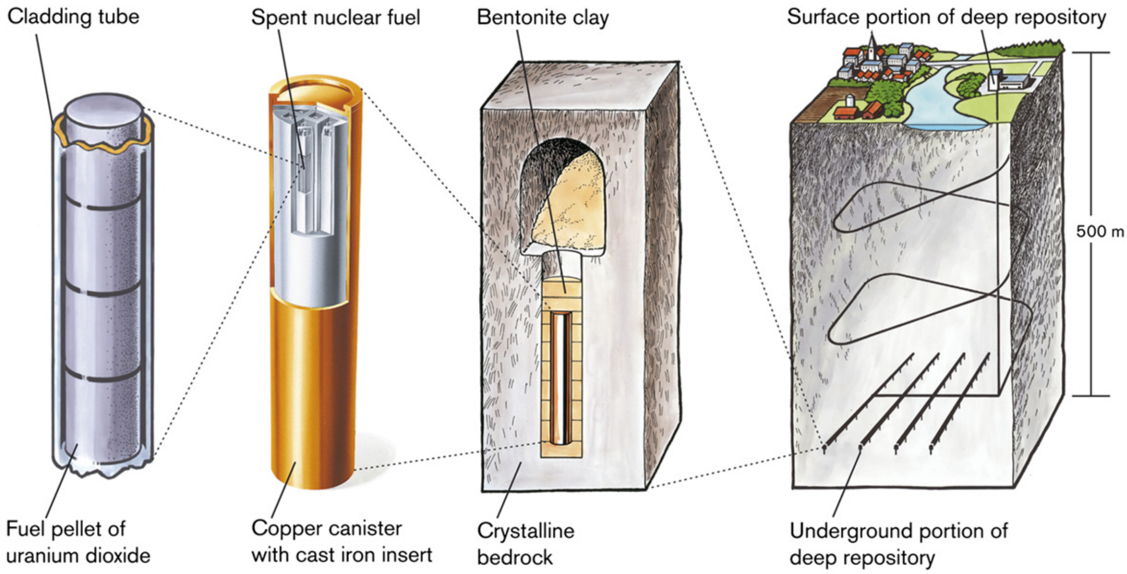

Fig. 1. Protection barriers in the Swedish method for nuclear waste management.

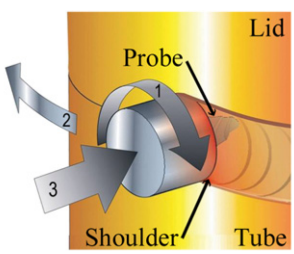

Fig. 2. Illustration of the friction stir welding process to seal copper canisters.

which is clamped with a force of 3200 kN. The lid is pressed down with a force of 390 kN.

All welds are carried out under force control, i.e. constant axial force (input 3 in Fig. 2) throughout the weld cycle. For more information on the machine, see e.g. Ronneteg, Cederqvist, Rydén, Öberg, and Müller (2006).

2.2. Available control and measurement signals

One reason for the fast (and growing) implementation of FSW in industry is that the method has few input variables. The input parameters, that can be modified during the copper canister welds, are listed according to Fig. 2; 1. tool rotation rate, 2. welding speed along the joint, and 3. axial force (controls the position of the tool in relation to the canister surface, i.e. the tool depth). The measured variables are the welding (tool) temperature, the torque required by the spindle (that drives the tool rotation) to maintain the tool rotation rate, and the depth of the tool into the welded material.

There are also some elementary relationships between the signals that are important to understand. The tool rotation rate multiplied with the spindle torque is equal to the power input in units of kW. In addition to this, the heat input (J/mm) can be derived by dividing the power input with the welding speed. Both quantities are closely correlated to the welding (tool) temperature.

2.3. Argon shielding gas

Upadhyay and Reynolds (2010) investigated the effects of varying thermal boundary conditions by for example, welding under water. Similarly, the process stabilizing effect that argon gas has on the copper canister welds, was described by Cederqvist, Reynolds, Sorensen, and Garpinger (2010). Today, all welds are produced in argon gas by placing a gas chamber over the tool. The main reasons for using argon as a shielding gas are to achieve a weld zone with minimal oxide inclusions and to get a more robust process, partly thanks to less shoulder wear. As a direct result of this, the spindle torque variations are smaller and the controller will thus have an easier task obtaining its objectives.

2.4. Temperature measurements and process window

Measuring the welding temperature is not a trivial matter. The sensors, so called thermocouples, should ideally be placed such that the temperature response has as little delay as possible, but they should also correlate well with weld quality. Typically, the sensors are placed in the welding tool. Fig. 4 shows the tool in profile and the location of the three thermocouples currently used to measure the welding temperature (ID and OD stands for inner and outer diameter, respectively). All three thermocouples have reaction times that are less than 620 ms, and calibration errors of 0.1%, i.e. $<1\,^{\circ}$C. The probe sensor is situated 10 mm from the surface, while the shoulder ID and OD sensors are only 1 and 2 mm away, respectively. It should also be mentioned that the probe material is a nickel-based superalloy called Nimonic 105. The shoulder material, on the other hand, is made of a tungsten alloy called Densimet D176. Depending on the sensor position and the probe/shoulder material, the measurement signals will have slightly different dynamic relations to the input signals of the process. In terms of delay, the probe temperature takes the longest time to react, followed by the shoulder OD and then the shoulder ID, which has the least dead time.

If the welding temperature gets too high, for a longer period of time, there is a risk for probe fracture resulting in a rejected canister with both extensive and expensive work to take out the nuclear waste. Similarly, too low temperatures may result in discontinuities in the weld (so called wormholes) that could, depending on size, also lead to a rejected canister. It is, in other words, very important to keep the temperature within this, so called, process window. The process window for FSW on the copper canisters is roughly between 790 and 910 $^{\circ}$C (probe sensor), which has been determined through minimum and maximum