Electro-thermo-mechanical simulation of the longitudinal HFI-welding process of carbon steel tubes

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***Abstract*—This paper addresses the experimental simulation of the longitudinal HFI-welding process of carbon steel tubes. Therefore, the experimental setup facilitates two plain sheets of the tube material. These sheets were moved towards each other while they were conductively heated by a high frequency electrical current. The heated sheets are pressed together to form a pressure weld. Therefore, the approach does not require a tubular specimen or the whole process line to perform experimental investigations of the tube welding process. The approach allows the representation of the current distribution across the tube edges, the subsequent heating and temperature distribution as well as the mechanical and most geometrical conditions of a corresponding tube welding process. Experiments with a HFI-tube welding rig provided reference data from the tube welding process. The temperature distributions during the welding process, the microstructure in the weld cross section as well as the resulting hardness distribution were intercompared between the tube welding process and the experimental simulation to verify the simulation approach.**

***Keywords*—high-frequency induction-welding (HFI), electrical resistance welding (ERW), longitudinal welding, tube manufacturing, pipe manufacturing**

I. INTRODUCTION

The tube or pipe production is one of the essential steel processing routes. Thereby, the welded pipe production represents the most common form of production. The highest output quantity of welded tubes is produced by inductive high-frequency welding (HFI-welding). This welding process is part of a coil material processing chain comprising uncoiling, coil joining, edge milling, coil forming, longitudinal welding, weld trimming, annealing, sizing and cutting. Therefore, experimental investigations with process parameter variations and different steels are complex and expensive. As a result, prior investigations focused mainly on the characteristics of the weld or the tube with different materials [1], [2] or on the heat treatment strategies [3]–[5] under constant welding conditions. The lack of systematic experimental studies on the influence of welding conditions in the HFI process also lead to missing recommendations for ideal process conditions and heat treatment strategies for HFI welded tubes.

II. SIMULATION APPROACH

The experimental setup (Fig. 1) facilitates two plain sheets of the tube material, which represent the joining partners, from which one is mechanically fixed on a driven sledge. The other sheet is attached to a static mounting. Both sheets were electrically contacted with each other via a electric bridge on one side and with the energy source at the other side so that a current I can flow through both specimens in opposite direction. During the process, the sledge moves both sheets towards each other with a speed v. From a defined position, the specimens were conductively heated by high frequency electrical current, provided by the aforementioned energy source. The heated sheets are then pressed together to form a pressure weld.

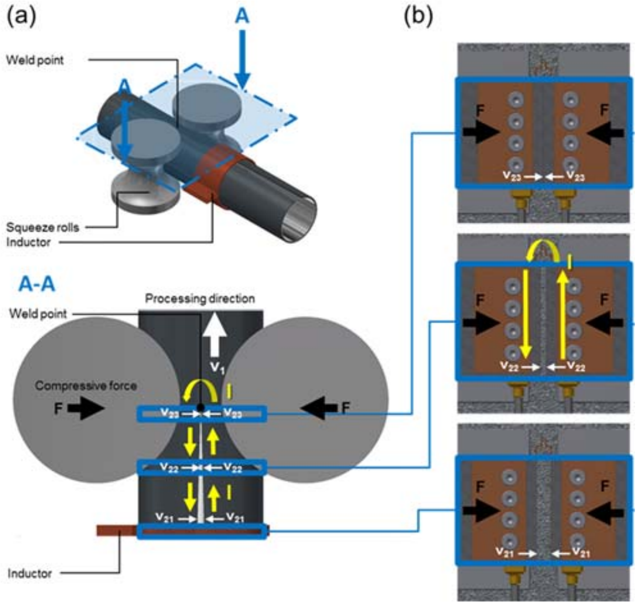


Fig. 1. Schematic illustration and working principle tube welding setup (a) and ETM-simulator (b).

The ETM-simulation directly reproduces critical tube welding parameters such as material (composition and microstructure), wall thickness, welding frequency, direction and distribution of the welding current and the dimensional compression of both specimens. Welding speed and entry angle can be converted into the speed of the sledge whereas the type, position and efficiency of the coil as well as current and voltage were transferred indirectly and have to be obtained experimentally or analytically.

III. EXPERIMENTAL SETUP AND PROCEDURE

The experimental investigations were carried out with S355 J2+N carbon steel from a single sheet. For the longitudinal welding, the sheets of 300 mm length were cut and formed to a tubular specimen. Subsequently, sacrificial steel tubes of the same cross-sectional dimensions were attached by TIG butt-welding. The specimens for the ETM-simulation were obtained by water-jet cutting and machining.

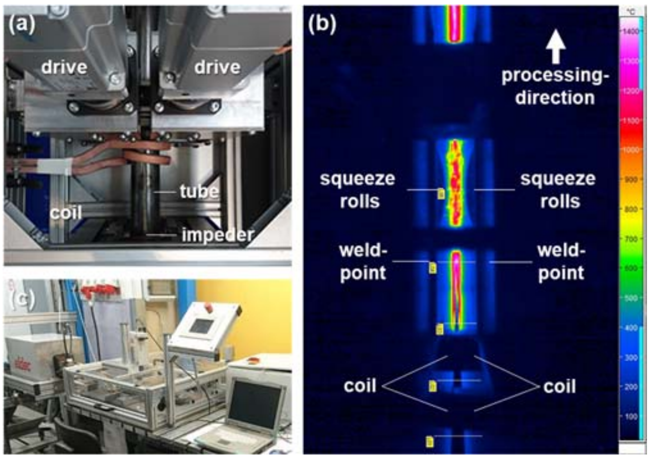


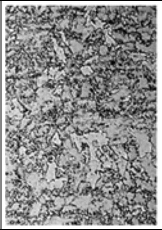
Fig. 2. Experimental tube welding setup (a), thermal camera recording to tube welding process (b) and ETM-simulator (c)

The tube welding test were performed with an experimental tube welding rig (Fig. 2) at a processing speed of 16 m/min, an entry angle of 2.8 °, and a frequency of 192.5 kHz. ETM-simulations were carried out at a frequency of 216.1 kHz with an experimental ETM-simulator. An EMAG Eldec SDF®225 generator served as the energy source for both welding processes. The surface temperature in both welding processes was measured using an InfraTec VarioCAM® inspect hr 680 thermal camera at the point of the fist contact of the tube or sheet edges. The obtained welds were investigated by a Carl Zeiss Axio Vert.A1 MAT optical microscope and an EMCO-TEST M1C 010 to obtain the microstructure and hardness.

IV. RESULTS

Pressure welding processes produce characteristic welds, comprising weld bead, weld junction, coarse and fine grained zones as well as thermomechanically affected zone. This applies also for both investigated welding processes.

TABLE I. COMPARISON OF RESULTING MICROSTRUCTURE IN DEFINED DISTANCE FROM CONTACT SURFACE

0.15 mm (Coarse grained zone)		**1.5 mm (Fine grained zone)**	
S0201 (Tube)	***PS0201-C1 (ETM)***	***S0201 (Tube)***	***PS0201-C1 (ETM)***
			

An experimental simulation should be able to produce a comparable microstructure and distribution of the latter. Table 1 provides an exemplary comparison of microstructures of tube and ETM-simulation welds.

The temperature distribution across the specimens and the resulting hardness through the sheet (Fig. 3) show a high conformity between tube and ETM-simulation. In both welding processes, deviations of the measured temperature occur within a distance of 1 mm from the joining surface at temperatures above 1000 °C due to the formation of scale. The hardness of the tube-specimen outside the HAZ is higher due to work hardening caused by the forming process. Within the HAZ the hardness profiles shows the same characteristic increase due to high cooling rates after welding. The drop of hardness in the weld junction is caused by carbon depletion and a higher porosity due to oxidation during the heating in the process.

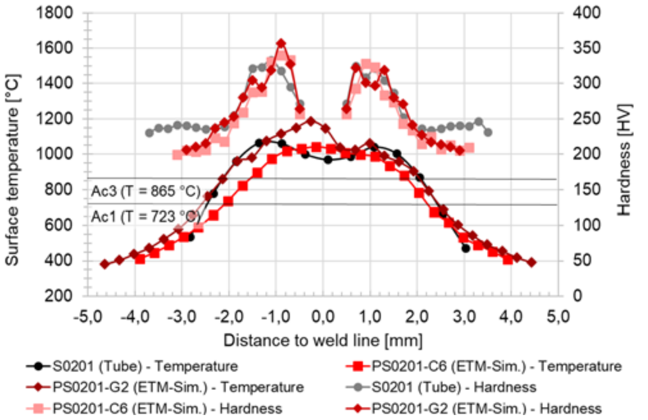


Fig. 3. Distribution of surface temperature and hardness in the sheet center perpendicular to to the weld seam for tube weld and two ETM-simulations

V. CONCLUSION

The ability of the ETM-simulation to represent the tube welding process, in terms of geometric and mechanical conditions, temperature distribution and compression of the joining partners as well as the resulting microstructure and hardness, has been demonstrated. Therefore, the ETM-simulation constitutes a suitable experimental approach and setup that allows systematic investigations of the factors influencing the HFI tube welding process without tubular specimen.

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