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Improving bonding quality of underwater friction stitch welds by selecting appropriate plug material and welding parameters and optimizing joint design

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ABSTRACT

Friction stitch welding of S355 steel was conducted under wet conditions to study the bonding quality. The effects of plug material, joint design, and welding variables on the weld defects, microstructural characteristics, hardness levels, and tensile properties were investigated. The underwater stitch welding performed with a S355 steel plug exhibited visible bonding defects at the weld interface, while the weld with LF2 as the plug material yielded a qualified joint without cracks or discontinuities, provided the plug and hole geometries were well-designed. The LF2-plug-stitch weld contained more upper bainite and fewer lath martensite grains, which was consistent with the substantially decreased hardness values in the weld metal. The joint was designed with large initial contact area and gap between the plug and hole, so a higher amount of heat was generated when welding was started. Further, the welding time was extended from 11 to 16 s, resulting in a larger heat affected zone and the flow of the plasticized (or squeezed) material was improved too. Stitch welds realized with a 40 kN forging force exhibited better ultimate tensile strength and elongation than those with a 35 kN forging force, when the other conditions were kept constant.

1. Introduction

Underwater damage in marine structures, undersea oil pipelines, and platforms needs to be properly addressed, in order to extend the service life of such infrastructure. The maintenance of such structures usually requires localized underwater repair operations [1]. Although, there are several accepted methods for underwater repair operations, underwater welding is one of the most promising methods.

An increasing number of countries are getting involved in exploiting deep-sea resources by utilizing marine oil/gas fields, and conditions under which undersea structures and pipelines are serviced or assembled are becoming increasingly complex. In current underwater arc welding processes, an unstable arc and bad shaping of the weld may occur under wet conditions at over 40 m depth. Further, since underwater welding at depths of over 50 m would be even more difficult, to ensure the safety of divers, the welding operation is usually automated in a dry cabin, and this results in high associated costs. Therefore, developing a new variant of underwater welding and repair technology that is suitable for operations at underwater depths of over 50 m is of great value.

Some new technologies including friction based underwater welding have been proposed to handle the operations over the depth of 50 m [2,3]. Friction stitch welding, which is illustrated in Fig. 1, is an innovative friction welding process. It is a practical solid-state repair method for repairing long cracks in marine structures and undersea oil pipelines. In this process, when repairing a long crack, a stitch weld is fabricated by overlapping a number of friction taper plug welds at a given distance along a pre-defined path [4]. Friction taper plug welding (FTPW) is a combined drilling and filling process, which involves drilling a blind hole and then forcing a rotating tapered consumable plug to fill the hole concentrically [5–7]. Friction stitch welding circumvents the adverse effects associated with an increase in the ambient pressure with underwater depth, and the process can be easily automated [8,9]. Therefore, this process can be considered to be a breakthrough in deep water welding.

So far, several studies on FTPW, particularly those conducted in air, have been reported: The possible bonding mechanisms, influence of process parameters on the bonding quality, and practical applications of the method have been investigated. Pinheiro [10] focused on the metallurgical and mechanical properties of similar and dissimilar welds fabricated by FTPW. It was found that qualified joints could be produced in air in a wide operating window. Meyer [11] found that as a result of sequential welding, the former welds were subjected to heat treatment

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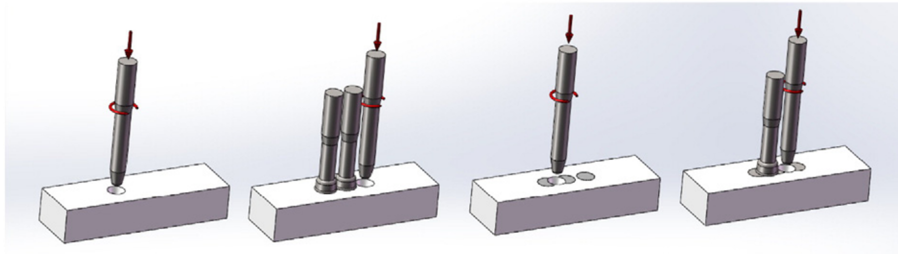

Fig. 1. Schematic illustration of the friction stitch welding process.

during the subsequent welding processes, which reduced the maximum hardness values when friction stitch welding was performed in air. In addition, the welding results for S235 steel in air met the classification society requirements for repair cracks in ship hulls [11]. Chludzinski found that the fracture toughness of FTPW joint is much lower than the base metal (BM) and is hardly influenced by varying the axial force in all his cases [12]. However, investigations on underwater friction stitch welding (or FTPW) have rarely been reported.

In our previous study, defects were observed in the bonding line at the corner when friction stitch welding was performed in underwater wet conditions, where S355 low-alloy steel was used both as plug and BM [13]. The hardness values of the joints (up to 490 HV_{10}) were too high to finish the subsequent welding operations well. Drilling for the next weld spot of stitch welding was difficult since (a) feeding the drill into such a hard material was difficult, and (b) the uneven hardness that the drill encountered on different sides made the drill bend towards the soft sides, thereby reducing the accuracy of the hole shape and becoming a major cause of defects at the corner.

The objective of this work is to improve the bonding quality of the friction stitch welds in underwater conditions. In Section 2, the factors influencing the bonding quality are analyzed in detail, and some feasible solutions for improving the bonding quality are proposed. Experiments designed to prove the solutions suggested in Section 2 are described in Section 3, and the results are discussed in Section 4.

2. Factors influencing bonding quality and proposed solutions

The bonding quality is mainly dependent on the proper selection of materials, joint designs, and welding variables [14].

2.1. Plug material selection and stitch welding sequence

The underwater friction taper plug welds exhibited high hardness values when S355 was used as both the plug and base materials, because the welds were quenched by the surrounding water. As mentioned previously, high hardness will worsen the weld quality. To reduce the hardness of the welds, ASTM A350 LF2 steel (LF2 for short), which has a relatively low hardness and good weldablity, was employed as the plug material. To balance the uneven hardness on the different sides of the drill, an optimized stitch welding sequence, in which every other spot was welded, was selected.

2.2. Joint design

Meyer showed that the hole shape and plug geometry exert a major influence on the heat input from friction and material flow, which further influence the ability to realize bonding all around the joint [11]. Xu found that the plug and hole configurations affect the quality of the welding product through stress state and temperature distribution

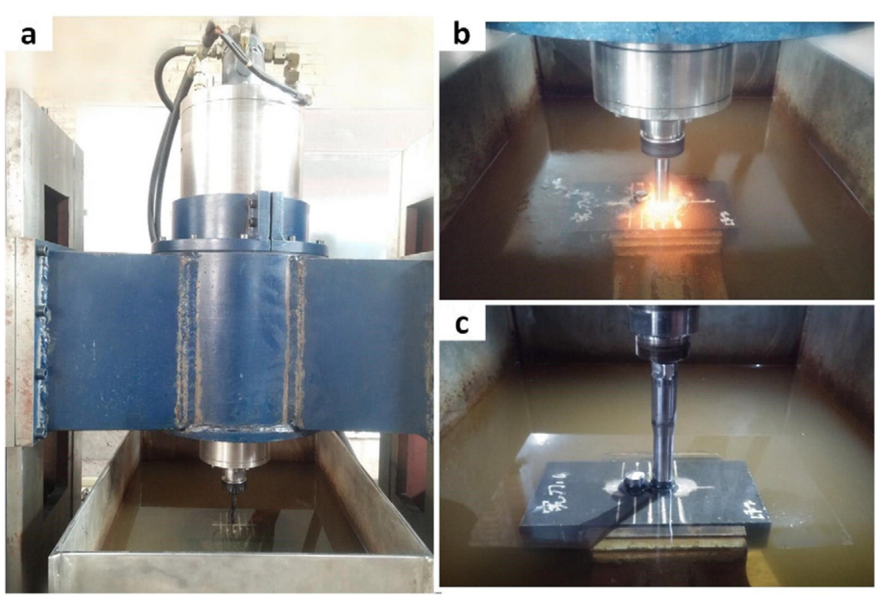

Fig. 2. Friction stitch welding equipment and welding process in the underwater wet conditions: (a) friction stitch welding equipment, and (b) and (c) location of the workpiece in the vice in the water tank.