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Numerical simulation of the effects of various stud and hole configurations on friction hydro-pillar processing

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ABSTRACT

This paper focuses on the effects of stud and hole configurations on weld defects in friction hydro-pillar processing (FHPP). Various configurations of the stud and hole are designed and all welds are performed by using a self-developed high-performance platform with the same welding parameters. The experimental results indicate that the defects usually appear at the bottom of the hole, but the upper region bonds well. The quality of welded joints is deeply affected by the bottom filling which is called initial stage. Therefore, the finite-element method (FEM) is employed to simulate the initial stage of FHPP. The simulated results agree well with those of the experiments. The results indicate that the geometry of the hole influences the welding quality more strongly than the shape of the stud and that weld samples with a rounded corner at the bottom of the hole bond well. Moreover, different shapes of the studs cause different stress states and temperature distributions, which also influence the quality of welded joints.

1. Introduction

Welding technology is widely used to repair and maintain components during manufacture or lengthy service. The most common welding process is fusion welding, which is often employed for repair and refurbishment because of its high quality [1]. However, fusion welding has caused some problems such as grain growth, hydrogen embrittlement, and slag trapping [2]. Moreover, the severe conditions such as underwater also limit the usefulness of this process [3–5]. Thus, friction hydro-pillar processing (FHPP), which is derived from friction welding, has caught the attention of many scholars [6,7]. As a solid-state joining process, FHPP affords the advantages of friction welding, such as low cost, no defects relative to melting, and high efficiency [2,8,9]. The main features of this novel process are illustrated in Fig. 1. As shown, the FHPP technique involves a rotating consumable rod (cylindrical or conical) and an essentially circular hole. When the rod reaches the pre-set speed, the sliding surfaces interact with each other under an applied load to continuously generate a localized plasticized layer. The consumable member is fully plasticized across the bore of the hole and through the thickness of the workpiece. The plasticized material develops at a faster rate than the axial feed rate of the consumable rod, which means that the frictional rubbing surface rises along the consumable rod to form a dynamically recrystallized deposit material. The plasticized material at the rotational interface is maintained in a sufficiently viscous condition for hydrostatic forces to be transmitted both axially and radially to the inside of the hole, enabling the creation of a metallurgical bond [2].

Since FHPP was first developed by TWI [7], this technology was widely viewed as an attempt to replace fusion welding for joining and repairing thick sections of structures. Several studies have since indicated a relationship between the welding parameters and mechanical properties of this proposed technology. In 1993, Thomas and Nicholas [10] presented additional advantages of the FHPP by focusing on its application in the industry for joining and repairing thick steel components. In the same year, the patent on this process was granted to TWI [11]. The researchers stated that as in all friction welding processes, the weld material needed for FHPP is relatively small and the process is easily automated for mass production. Nicholas [12] also first reported the microstructure and mechanical properties of FHPP. This comprehensive report covered the parallel hole configuration as well as the taper hole arrangement. The author found that materials that do not exhibit adequate plastic flow characteristics often responded much better to a tapered joint design. Moreover, because the consumable rod experienced a significantly hot process during welding, a very refined hot-worked microstructure was reported. For example, with mild steel, depending on the welding

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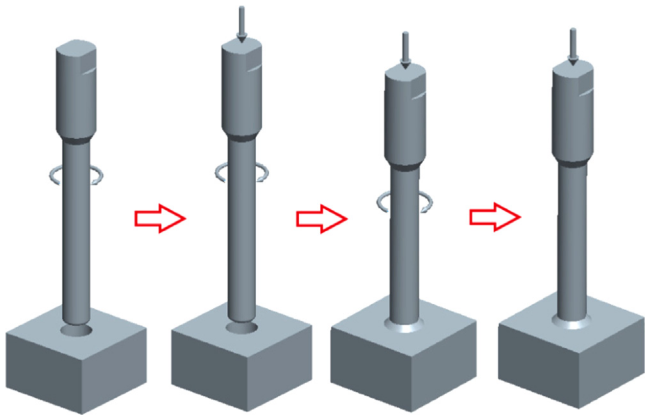

Fig. 1. Schematic illustration of FHPP.

parameters, the study found either a very refined microstructure throughout the weld specimen or refined regions that did not undergo layer shearing. Thomas [13] investigated the influence of additional gas shielding on FHPP and its properties. He discovered that the gas enabled superior weld properties at lower burn-off rates and avoided oxidization in the gaps between the plates. Recently, Chludzinski et al. [14] studied the fracture toughness of FHPP in C–Mo steel. In their work, the fracture toughness of the weld was compared with that of base metal. Moreover, the relationship between fracture toughness values and axial force applied during the entire welding process was studied.

Despite the wide-ranging potential applications of FHPP, welding produced by FHPP has not been extensively investigated. Thus far, there are very limited studies using a finite-element method (FEM) to simulate the process of FHPP. Moreover, information on the effects of various stud and hole configurations on FHPP is limited in scope. Through numerical simulation, the mechanism of the FHPP process can be analyzed further. Furthermore, defect-free, optimized stud and hole geometries can be selected by using the FEM. Hence, it is necessary to analyze the process of FHPP by utilizing the finite-element theory.

Accordingly, in this study, various stud and hole geometries are designed to select the optimized configuration. All welds are conducted by using self-developed high-performance welding equipment. The experiments indicate that bonding at the bottom section is crucial to the quality of welded joints. Therefore, the FEM is employed to estimate the welding process of FHPP for typical cases in the initial phase. The simulated results are verified by the experimental results.

2. Experimental procedure

Welding was performed using a hydraulically powered machine. This entire welding system primarily consisted of four major components: a hydraulic unit; a welding head, including a hydraulic fixed motor and a cylinder; valve blocks; and a control system. Its maximum power is 90 kW, and the maximum axial force is 60 kN. The maximum rotary speed of the hydraulic fixed motor is 8000 rpm, and the maximum torque is 120 Nm.

To investigate the influences of various stud and hole configurations on FHPP, all experiments were divided into four groups. In group A, the flat-bottomed hole in which the diameter and depth were 16 mm and 20 mm, respectively, a 30-mm-thick substrate was used with rods with different tip designs, as shown in Fig. 2(a). In group B, the geometries of the studs and holes were the same as in group A, except for a 1 mm rounded corner at the bottom of the hole, as shown in Fig. 2(b). In group C, both hole bottoms and stud tips were used with a 2 mm rounding. The difference between them was that the gap between the hole and the stud varied from 0.5 mm to 2 mm in 0.5 mm steps, as shown in Fig. 2(c). Group D contained chamfer-bottomed holes and stud tips. The chamfered holes were consistently 45°, whereas the angles on the rod chamfer changed from 45° to 60° in 5° increments, as shown in Fig. 2(d). Table 1 presents the composition of the C–Mn steel that was used to manufacture both studs and substrates in this study. The same welding parameters were used for all specimens: rotation speed of 7000 rpm, applied downward force of 20 kN, forging force of 35 kN, and burn-off of 14 mm. Once the welds were finished, they were

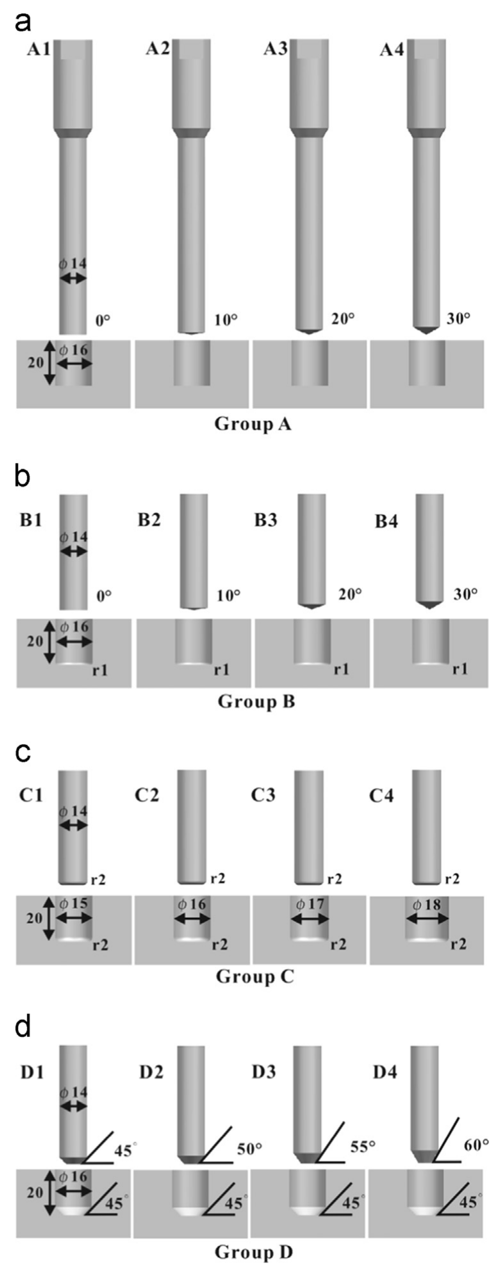

Fig. 2. (a) Stud and hole configurations. (b) Dimensions of group B. (c) Dimensions of group C. (d) Dimensions of group D.

Table 1
Standard chemical composition in wt% of material.

Chemical composition	C	Si	Mn	P	Al	N	Nb	Fe
C–Mn steel	0.18	0.5	0.6	0.035	0.015	0.02	0.04	Balance