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Static and fatigue behavior of plug-welded dissimilar metal welds between carbon steel and austenitic stainless steel with different thicknesses

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Abstract

Background: Plug welding was used on the parts of the structure in which spot welding cannot be implemented, such as the complex structure and the construction with the profile stiffener. The objective of the present work is to define the static and fatigue behaviors of the plug-welded dissimilar metal welds between carbon steel and austenitic stainless steel with different thicknesses because the detailed recommendations on it were limited.

Methods: Carbon steel SS400 with a thickness of 3.0 mm and 1.0-mm-thick austenitic stainless steel SUS304 were plug welded using varied hole diameter in a range of 7 to 13 mm where the welding current and the diameter of welding wire were kept constant at 80 A and 1.0 mm, respectively. The welding joints were exposed to tensile shear tests, and the transition of interfacial fractures to tearing fractures was defined as the optimum condition. Tensile peel, fatigue, and corrosion fatigue tests were carried out on the optimum specimens.

Results: The optimum plug welding joints were obtained at the hole diameter of 8 mm where the tensile peel and tensile shear load bearing capacity were 8.6 and 17.2 kN respectively. The endurance limit of fatigue conducted in air was 2 kN, whereas corrosion fatigue samples at this load fail at about 1,000,000 cycles.

Conclusion: AWS's formula for plug weld can be applied to the plug-welded dissimilar metal welds between carbon steel and austenitic stainless steel with different thicknesses. Endurance limit of this joint in corrosive environments is about half of the endurance limit in normal environments.

Keywords: Fatigue; Carbon steel; Austenitic stainless steel; Plug welded; Dissimilar metal welds

Background

Welding of dissimilar metals between carbon steel and stainless steel has been widely used in engineering practice over the years. It is more economical compared to the ones made of stainless steel only. The importance of corrosion resistance in the structures is also the reason for the implementation of dissimilar metal welds. Dissimilar metal weld is generally more challenging and often causes problems due to differences in the physical, mechanical, and metallurgical properties of the base metal to be joined.

The stiffened thin plate structure, where the thinner plate is reinforced by a thicker plate called a frame, has been claimed as being a cost-effective way of achieving a high-performance vehicle structure (Gean et al. 1999). This structure is generally welded by resistance spot welding due to its advantages in welding efficiency and suitability for automation (Hou et al. 2007). The parts of the structure in which spot welding cannot be implemented, such as the double sheeting structure, complex structure, and the construction with the profile stiffener, plug welding was applied instead of spot welding. Welding schedule of plug welding has been offered by American Welding Society (AWS) (2004) and previous study (Tsuruta et al. 1952). According to this recommendation, the weld quality is achieved when the hole diameter of plug welding is $8 + t$ (in mm), where t is the thickness of the joined plate (in mm). It is very useful in finding good weld schedules for equal-thickness welding, but confusing in that for unequal-thickness plate welding and generally developed by and practiced within individual manufacturers (Agashe and Zhang 2003). Some of them use the thickness of thinner material, and others use the average of joined material thickness in that empirical formula. There

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are a lot of scientific papers dealing with static and fatigue behaviors of spot-welded dissimilar metal joints (Alenius et al. 2006; Hasanbasoglu and Kacar 2007; Jamasri et al. 2011; Vural et al. 2006), but only a few studies have been published concerning those of plug welded. The objective of the present work is to investigate the static, fatigue, and corrosion fatigue of plug-welded dissimilar metals between 3.0-mm carbon steel and 1.0-mm austenitic stainless steel.

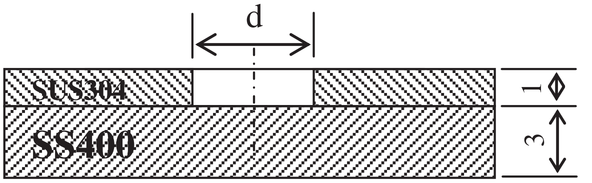

Figure 1 **Schematic of plug-welded dissimilar metal joint geometry.**

Methods

Materials and welding processes

Carbon steel SS400 with the thickness of 3.0 mm and 1.0-mm-thick austenitic stainless steel SUS304 were used in this study. The chemical composition and mechanical properties of the test materials are given in Table 1. Gas metal arc weld (GMAW) with argon gas and ER309L filler metal was performed on plug welding process using constant weld current, wire diameter, and weld voltage of 80 A, 1.0 mm, and 38 V respectively, while the hole sheeting diameter (*d*) was varied from 7 to 13 mm by 1-mm increments as illustrated in Figure 1.

Metallographic evaluation and mechanical test

The transverse section of weld passing through the weld nugget was prepared by standard metallographic procedure. Due to the nature of dissimilar metal welds, a two-stage etchant was used for etching. In the first stage of etching, 2.5% alcoholic nitric acid solution was used to reveal the microstructure of carbon steel side. The microstructure of austenitic stainless steel side and weld metal were revealed using 10 ml nitric acid, 20 ml hydrochloric acid, and 30 ml water. Microstructure investigations were carried out using an optical microscope.

Static tensile shear and peel tests were conducted and the failure mode, weld size, and load to failure were recorded. The samples were made according to the French standards A 87-001 and NF A 89-206 as shown in Figure 2.

The corrosion fatigue testing was performed in laboratory conditions using a 40-kN servohydraulic Shimadzu testing machine (Kyoto, Japan) with a software package specifically designed for running fatigue tests. All tests were carried out at room temperature with stress ratio and frequency of 0.1 and 8 Hz, respectively. The test sample was made according to the French standard A 03-405 as shown in Figure 3. It was similar to the samples used from a work which was carried out by Gean et al. (1999).

Table 1 The chemical composition (wt.%) and mechanical properties of test materials

	SS400	SUS304
Element		
C	0.054	0.076
Ni	0.073	8.183
Cr	0.044	18.107
Mn	0.225	0.252
P	0.094	0.031
Si	0.154	0.389
Yield strength (MPa)	245	305
Tensile strength (MPa)	388	670

The corrosion chamber as shown in Figure 4 was used in the corrosion fatigue tests. The chamber was located around the test specimen so that the part of the corrosion fatigue specimen was exposed in stagnant natural seawater of pH about 8.0 with a salinity of 34.5 g NaCl/l. Fatigue tests in air were also conducted as a comparison.

Electrochemical tests

The corrosion rates of the raw material and plug-welded surface were evaluated using Potensiostat/Galvanostat Model 273 (Princeton Applied Research, Oak Ridge, TN, USA). The samples were mounted in epoxy to expose only one surface with an area of 133 mm^2 for electrochemical tests. A saturated calomel electrode (SCE) was used as the reference electrode and a platinum wire was

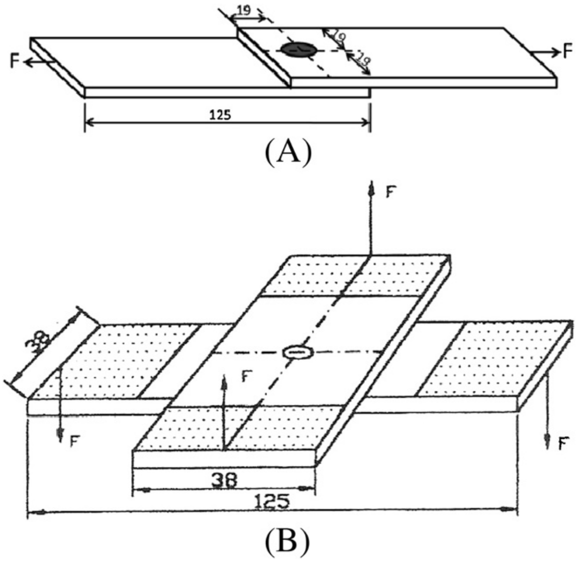

Figure 2 **Dimension of specimens (dimensions in mm). (A)** tensile shear test **(B)** tensile peel test.

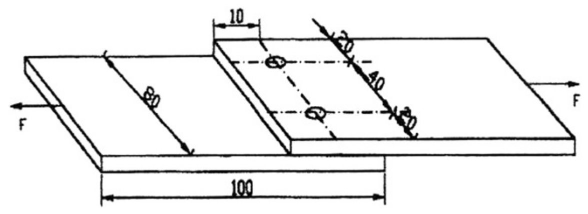

Figure 3 Fatigue specimen (dimension in mm).

used as the counter electrode. All electrochemical tests were carried out at room temperature. The polarization was conducted in natural seawater at a potential scanning range from −800 to +300 mV with a speed of 20 mV/min. Tafel lines were drawn on corresponding graphical plot of E versus log I to obtain the corrosion current (I_{corr}) value.

Results and discussion

The most important factors that affect plug weld quality are strength, depth, and area of weld penetration (American Welding Society 2002). In order to determine weld quality of plug-welded dissimilar materials, the strength of weldment was also determined. Structures employing plug weld are usually designed so that the welds are loaded in shear when the parts are exposed to tension or compression loading. In some cases, the welds may be loaded in tension, where the direction of loading is normal to the plane of the joint, or a combination of tension and shear (Hasanbasoglu and Kacar 2007).

In this study, the effects of hole diameter on the tensile shear load bearing capacity of the plug-welded dissimilar metals joint are shown graphically in Figure 5. It is found that tensile shear load bearing capacity of welded materials increased with increasing hole diameter.

The enhancement in tensile shearing load bearing capacity of weldment with increasing hole diameter was primarily attributed to the enlargement of penetration size including the depth and diameter of penetration.

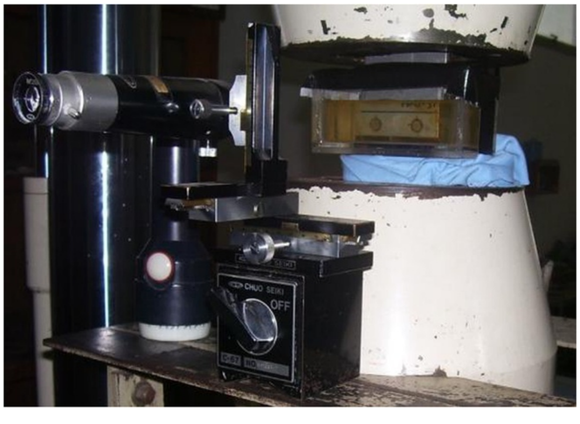

Figure 4 The corrosion chamber used in the corrosion fatigue test.

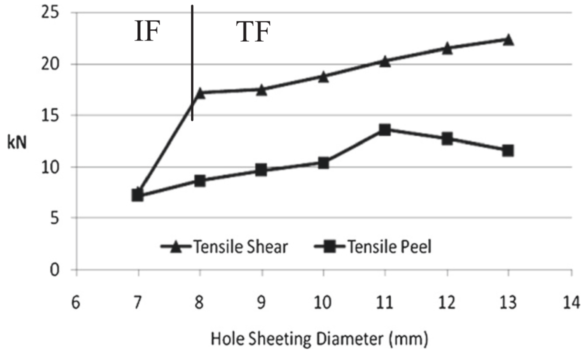

Figure 5 Tensile shear and tensile peel load bearing capacity of welded materials.

Plug-welded material with a hole diameter of 7 mm had low tensile shear strength bearing capacity due to low penetration size. It had a penetration diameter of 4.8 mm and a penetration depth of 0.7 mm (Figure 6A) which led it failed in interfacial fracture mode (IF) as shown in Figure 7A. Tensile shear load bearing capacity would increase if the hole diameter was increased to 8 mm due to increasing penetration diameter to 6.8 mm and penetration depth to 1.3 mm as seen in Figure 6B. It caused the tearing failure mode (TF) as illustrated in Figure 7B. Therefore, because the tearing failure mode

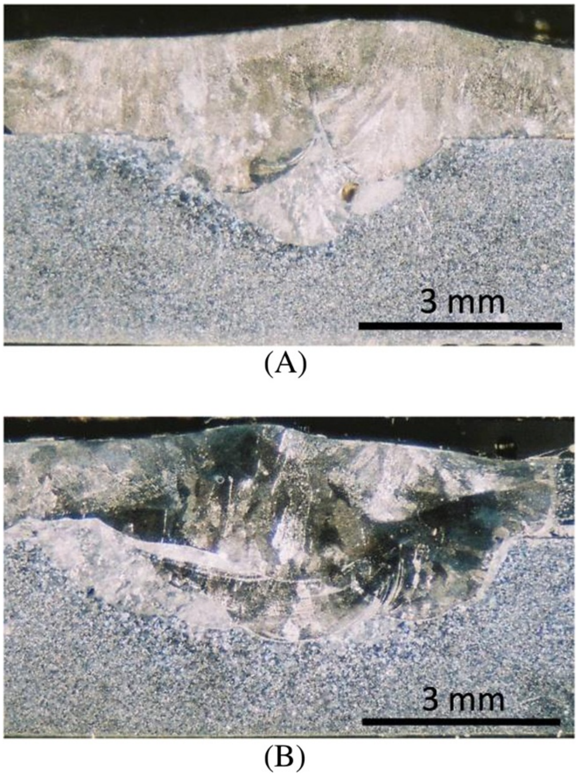

Figure 6 The macrostructure of plug weld with hole diameter. **(A)** 7 mm and **(B)** 8 mm.

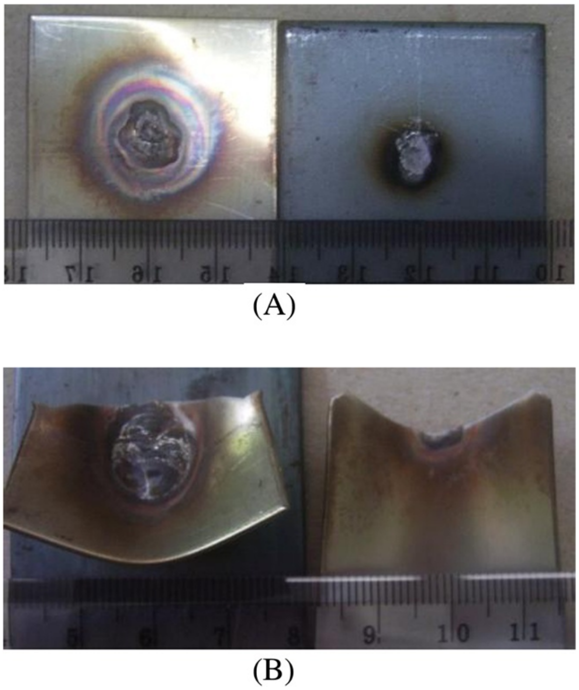

Figure 7 The fracture mode of tensile shear test samples. **(A)** 7 mm, and **(B)** 8 mm.

was guaranteed, hole diameter of 8 mm was designated as the critical hole diameter which ensured the reliability of plug-welded dissimilar metal between 3-mm-thick carbon steel and stainless steel with a thickness of 1 mm. According to AWS's recommendation, the minimum hole diameter required to ensure reliability of plug-welded materials based on the thinnest joined materials of 1 mm is 9 mm, while based on the average joined material thickness of 2 mm is 10 mm. However, as can be seen from Figure 5, even plug-welded material with 8 mm hole diameter in this study failed in the tearing mode.

Based on the result of the tensile shear test which determined the specimen with a hole diameter of 8 mm which was the optimum plug-welded joint, fatigue and corrosion fatigue tests were performed on these specimens. The *S-N* curves, the results of corrosion fatigue and fatigue tests of the plug-welded joints are presented in Figure 8. All data points belong to a mean value of three tests. As shown in Figure 8, while the load range decreases, the fatigue life of the specimen increases as expected. The fatigue specimens in air condition exhibited higher fatigue strength than those in corrosive condition, especially at low stress. There was no inclination going to a specific endurance limit for fatigue in air and corrosion fatigue. The fatigue class (FAT) which was identified by the characteristic fatigue strength of the detail at two million cycles (Hobbacher 2003) for fatigue in air was 2 kN, whereas corrosion fatigue samples at this load fail at about 1,000,000 cycles. It shows that sea water environment decreases remarkably the fatigue strength of the plug-welded dissimilar metals between carbon steel and austenitic stainless steels.

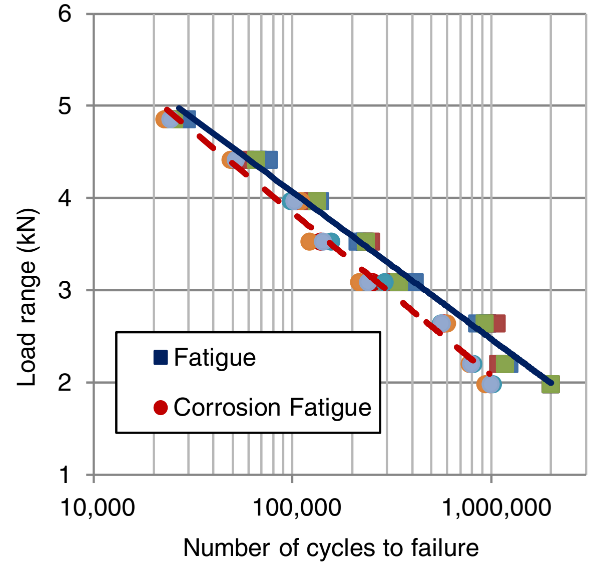

Figure 8 Comparison of corrosion fatigue and fatigue test results.

Failures of fatigue in air and corrosion fatigue of plug-welded specimens are in the form of tearing fracture mode as seen in Figure 9. The fatigue cracks started in the weld metal adjacent to the penetration area. After initiation, the crack propagation occurred through the thickness of the thinner sheets and continued propagating through the width of the thin sheet. Finally, this mechanism led to the tearing fracture mode as seen in

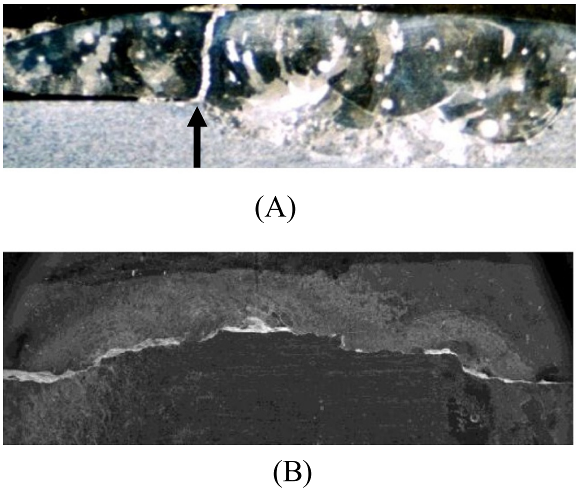

Figure 9 Failure mode of fatigue (A) Crack location and (B) final failure of corrosion fatigue and fatigue in air.

Figure 9B. This phenomenon is different from fatigue behavior of spot-welded equal sheet thicknesses which were observed by Vural et al. (2006), Alenius et al. (2006), and Jamasri et al. (2011). They found that the spot-welded dissimilar metal fatigue failures were the interfacial or pullout fracture.

The corrosion fatigue strength weakening was definitely affected by hydrogen embrittlement (HE). It was revealed as microscopic ductile fracture, resulting from hydrogen concentration at crack tips leading to hydrogen-enhanced slip. Figure 10 shows the micrographs of the crack initiation, while Figure 11 shows those of the crack propagation of corrosion fatigue and fatigue in air, which was tested at the same stress level and frequency. They show that the specimens are susceptible to the hydrogen embrittlement in natural sea water. In the fatigue specimen, each striation was regularly formed and roughly triangular in shape. In the corrosion fatigue specimen, on the other hand, striations were irregularly shaped and less obvious compared to those of the fatigue specimen. Many articles have been published to describe this

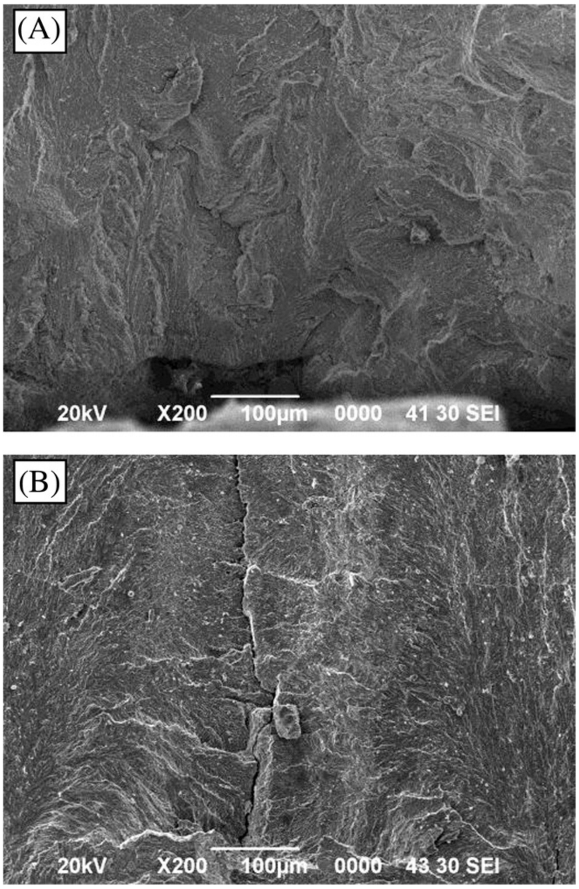

Figure 10 Crack initiation zone. (A) Corrosion fatigue and **(B)** fatigue in air.

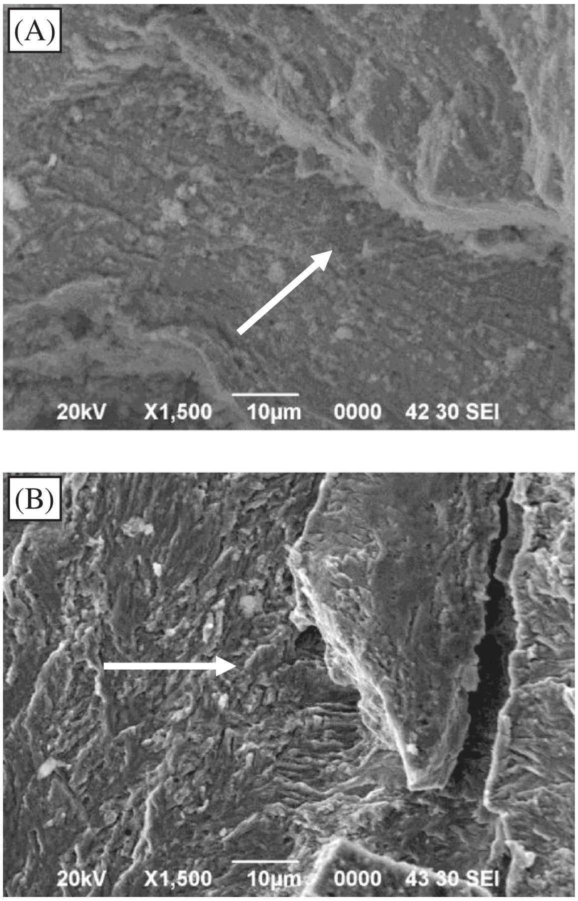

Figure 11 Crack propagation zone. (A) Corrosion fatigue and **(B)** fatigue in air. The arrows indicate the crack growth direction.

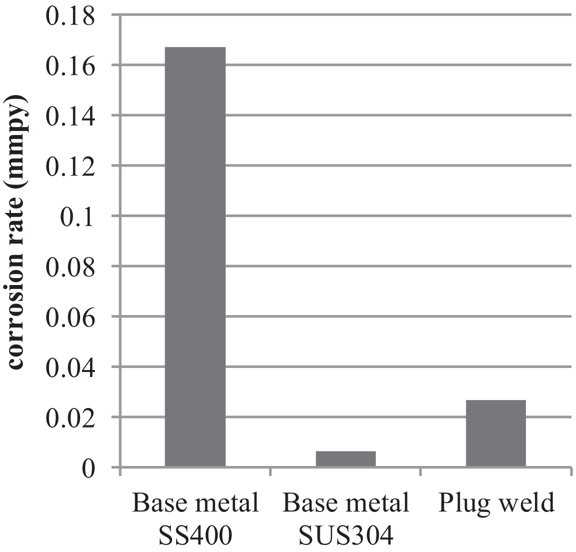

Figure 12 Corrosion rate of the weld metal.

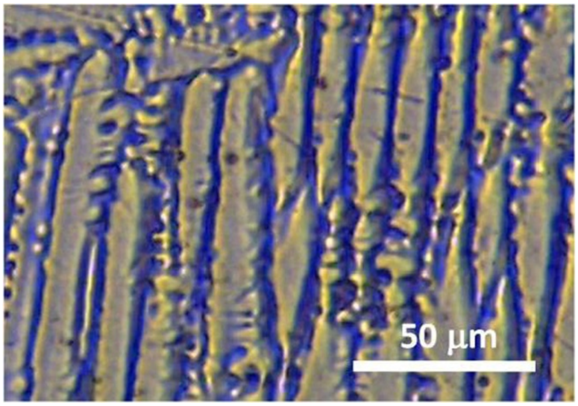

Figure 13 Microstructure of the weld metal.

phenomenon, although they have not agreed on the mechanism of HE (Kim et al. 2003).

HE phenomenon was clarified by the fact that the cracks occurred in the weld metals which have inferior corrosion resistance compared with the base metal (Figure 12). This is due to the fact that the weld metal has an inhomogeneous and dendritic microstructure (Figure 13) with micro-segregation of major elements (i.e., Cr and Ni) as well as minor elements (i.e., S and P) at δ-γ interface boundaries. The non-uniform alloying element concentration around ferrite particles plays a major role in determining the corrosion behavior of such weld metals (Kim et al. 2003). Figure 13 also shows the microstructure of a weld metal consisting of the delta ferrite and austenite phases. Delta ferrite leads to detrimental effects on the corrosion resistance (Pujar et al. 2005).

Conclusions

Because the tearing failure mode was guaranteed, the optimum plug welding joints were obtained at the hole diameter of 8 mm where the tensile peel and tensile shear load bearing capacity were 8.6 and 17.2 kN, respectively. The endurance limit of fatigue conducted in air was 2 kN, whereas corrosion fatigue samples at this load failed at about 1,000,000 cycles.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

J participated in analysis of fatigue data, MNI contributed in micro-structure analysis, RS carried out the corrosion tests. All authors read and approved the final manuscript.

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