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Effect of post-weld heat treatment on friction welded joint of carbon steel to stainless steel

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ABSTRACT

1045 carbon steel was joined to 304 stainless steel by friction welding, and the joint was heat treated at different post-weld heat treatment (PWHT) temperature. The weld interface of as-welded joint was straight and obvious, whereas, it became indistinct after PWHT characterized by severe element diffusion. Chromium carbides such as $(Cr, Fe)_7C_3$ and Cr_7C_3 formed at the weld interface, the amount of which increased with the PWHT temperature increasing. In thermo-mechanically affected zone (TMAZ), the microstructure at carbon steel side of as-welded joint was quite heterogeneous, while it became homogeneous after PWHT at 400 °C. Analyses of fracture surfaces showed the amount of chromium carbide and the heterogeneous microstructure in TMAZ at carbon steel side were crucial factors in influencing fracture mechanism and properties of joints. Tensile strength and elongation of the joint were improved substantially after PWHT at 400 °C, which could reach up to the equivalent strength of stainless steel and elongation of carbon steel, because the microstructure became homogeneous to some extent and the amount of chromium carbides barely increased. The fracture mode also altered from quasi-cleavage fracture in as-welded joint to the combination of dimple fracture and quasi-cleavage fracture after PWHT.

1. Introduction

Carbon steel is widely used in manufacture structural components such as axles, crankshafts, couplings and gears, because of its attractive properties such as high strength, good wear resistance and low cost. Stainless steel, due to its superior corrosion resistance and good workability, is of great potential in manufacturing industry. The implementation of hybrid structures made of carbon steel and stainless steel can combine the advantages of two materials and allow design flexibility, which is full of promise in manufacturing industry (Sahin (2005)). However, it is a great difficulty to obtain sound dissimilar metal joints between carbon steel and stainless steel on account of the differences in chemical compositions and thermophysical properties.

It is known that during the welding of carbon steel to stainless steel, the element diffusion happens inevitably, which results in the formation of chromium carbide at the weld interface and the generation of decarburized zone at carbon steel side. Marashi et al. (2008) demonstrated the existence of decarburized zone deteriorated the mechanical properties of the joint greatly. The phenomenon was more serious in fusion welding for the high welding temperature history. Ul-Hamid et al. (2006) found that cracks initiated from the high hardness region at the weld interface and propagated along the decarburized layer adjacent to the carbon steel side after a comparatively short service time of arc welded joint of carbon steel to stainless steel. Solid-phase welding might provide a potential way to obtain high-quality joint of carbon steel to stainless steel since decarburized layer could be limited due to the relative low processing temperature. However, It was observed that there were formation of a large number of carbides at the weld interface and a decarburized zone with large width towards carbon steel side due to the quite long welding time when diffusion bonding of these two metals (Kurt (2007)), which revealed that diffusion welding could not offer a sound joint.

Friction welding process boasted distinct advantages to obtain high quality joint of carbon steel to stainless steel in that the process temperature was relatively low and the whole welding time was quite short, which could suppress the formation of chromium carbide and the decarburized zone. Considering the significant effects of welding parameters including friction pressure, friction time and upset pressure on the properties of the joints, the relationship between tensile strength and welding parameters was mainly focused. Sahin and Erol Akata (2004) suggested that the maximum tensile strength of carbon steel to stainless steel friction

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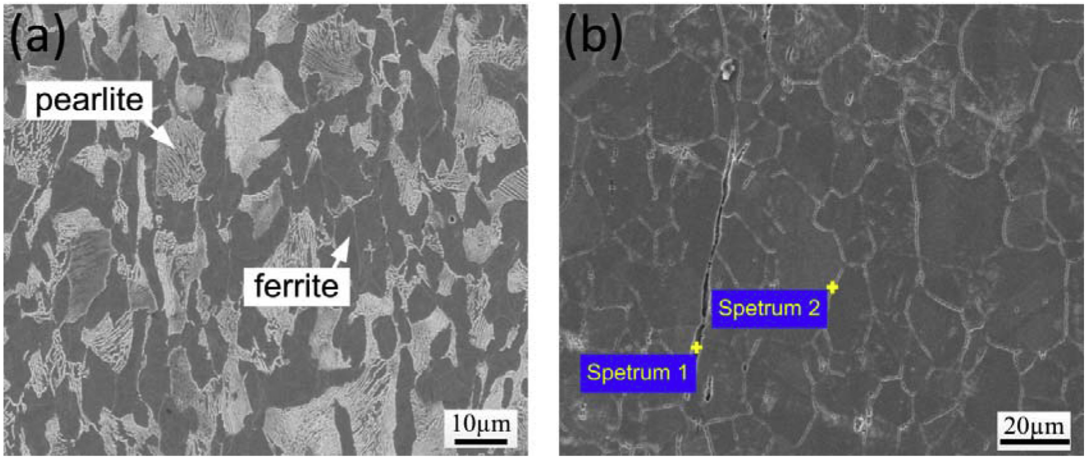

Fig. 1. Microstructure of base metals: (a) 1045 carbon steel and (b) 304 stainless steel.

Table 1
Nominal chemical compositions of the as-received base metals (wt.%).

Material	C	Cr	Ni	Si	Mn	Cu	Fe
304 stainless steel	0.08	18.0–20.0	8.0–10.5	1.00	2.00	0.03	Bal
1045 carbon steel	0.42–0.50	<0.25	<0.25	0.17–0.37	0.50–0.80	–	Bal

Table 2
Mechanical properties of 304 stainless steel and 1045 carbon steel.

Material	Tensile strength/σ_b (MPa)	Elongation percentage/ϵ (%)	Micro-hardness ($HV_{0.5}$)
304 stainless steel	880	29	310
1045 carbon steel	917	15	275

welded joint could be equal to that of carbon steel base metal by regression equation analysis method. Paventhan et al. (2012) found that the friction time had greater influence on tensile strength of the joints than other welding parameters. These studies had testified that the joints with quite high strength could be obtained by friction welding. However, all the friction welded joints of stainless steel to carbon steel still fractured at the weld interface with a low ductility. The fracture mode was analyzed by Ananthapadmanaban et al. (2009), which showed the main fracture mode was a brittle fracture mode. It was also reported by Paventhan et al. (2011) that $Cr_{23}C_6$ and Cr_7C_3 formed at the weld interface might be responsible for lowing fatigue, tensile, impact strength.

From the above researches, it was still of challenges to achieve satisfied joints of carbon steel to stainless steel with both high tensile strength and ductility just by friction welding. Dong et al. (2015) had reported that in friction welding of TiAl alloy to 40Cr steels, there was an agglomeration of C at the weld interface due to the formation of TiC. After post-weld heat treatment (PWHT), the agglomeration of C disappeared and the strength of the joint increased accordingly. Thus PWHT might be of benefit to improve the mechanical properties of joint because it could homogenize the microstructure especially at the weld interface.

The present work therefore investigated the potential for producing the joint with desirable mechanical properties in the post-weld heat treament process. The microstructure and mechanical properties of the dissimilar metal joints under as-welded state and PWHT state were studied and compared in detail to analyze the effect of PWHT process on microstructures, element diffusion and mechanical properties of the friction welded joint, and the effect factors on fracture mechanism and mechanical properties of the as-welded and heat treated joints were also evaluated.

Table 3
EDS analysis of δ-ferrite (spectrum 1) and base metal (spectrum 2).

Spectrum	Fe	Cr	Ni	Mn	Si
1	69.78	30.22	–	–	–
2	65.33	22.22	9.65	1.93	0.87

2. Experiments

2.1. Materials

1045 carbon steel and 304 stainless steel rods with diameter of 10 mm and length of 60 mm were used as the welding metals. The nominal chemical compositions and mechanical properties of the as-received base metals are listed in Tables 1 and 2 respectively. The microstructures of both the base metals are shown in Fig. 1. The microstructure of 1045 carbon steel base metal (BM) consisted of pearlite and ferrite, and ferrite was uniformly distributed along the pearlite grain boundaries. The microstructure of 304 stainless steel base metal not merely composed of austenite grains, and δ-ferrite existed in the form of stringers as well which could be identified by the result of the energy dispersive spectroscopy (EDS), as δ-ferrite is a Cr-rich phase, which was demonstrated by Chandra et al. (2012) and Shi et al. (2014). The EDS results are shown in Table 3.

2.2. Welding and PWHT process

Samples were welded on HSMZ-4 continuous drive friction welding machine with a maximum upset force of 40 kN which was suitable for welding the rods with small diameter (less