Materials Science & Engineering A 558 (2012) 572–578

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Microstructures and mechanical properties evolution during friction stir welding of SK4 high carbon steel alloy

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ARTICLE INFO

Article history:
Received 6 April 2012
Received in revised form
12 August 2012
Accepted 13 August 2012
Available online 19 August 2012

Keywords:
SK4 high carbon steel
Friction stir welding
Rotation speed
Microstructure
Mechanical properties
Fracture surface

ABSTRACT

Stir-in-plate welds were produced on 2 mm thick plates of SK4 high carbon steel alloy (0.95% C) using a load controlled friction stir welding (FSW) machine. The welding was carried out at a constant welding speed of 100 mm/min and different rotation speeds varied between100 and 400 rpm. The microstructure and mechanical properties of the weld metals were investigated. When FSW was carried out at 100 rpm, a duplex structure of spheroidal cementite and fine ferrite was formed and homogenously distributed in the entire stir zone. On the other hand, when the FSW was carried out at a rotation speed higher than 100 rpm, very fine pearlite and martensite structures were formed in the upper part of the stir zone and increased with the increasing rotation speed. Thin film of retained austenite was found in the microstructure of the weld metal stirred at 200 rpm and its volume fraction increased with further increasing in the rotation speed. Hardness values measured in the stir zone formed at 100 rpm were slightly higher than that of the base metal and homogenously distributed throughout the entire stir zone. Increasing rotation speed more than 200 rpm led to a sharp increase in the hardness values of the stir zone and maximum values around 800–820 Hv were attained at 400 rpm below the tool shoulder. Yield and ultimate tensile strengths of the weld metals increased with the increasing rotation speed, while elongation decreased. Fracture surface of the weld metal formed at 100 was similar to the base metal (BM) and exhibited only a microvoid coalescence dimple fracture, while that formed at 200–400 rpm showed a mixed mode of quasi-cleavage transgranular fracture and ductile dimple fracture mode.

1. Introduction

Friction stir welding (FSW) is a relatively new joining technique invented at The Welding Institute (UK) in 1991 [1] for mainly welding Al alloys [2–4]. The high quality Al welds produced by this technique encouraged researchers to extend its application to include magnesium [5,6], copper [7,8] and dissimilar group metal alloys [9–11]. Recently, high-melting temperature alloys, such as Fe, Ni and Ti based alloys, are also welded or structurally modified via FSW technique with achieving the same benefits that obtained from joining or modifications of low-melting temperature alloys [12–18].

High carbon steel alloys having spheroidal cementite in the ferrite matrix are used in many industrial applications because of their attractive strength and ductility balance at room temperature, high wear resistance and superplasticity at intermediate temperatures of 600–850 °C [19,20]. However, the weldability of these steels using conventional fusion welding processes is very poor due to the formation of microstructure in the weld joint highly susceptible to hydrogen induced-cold cracking. The susceptibility to the hydrogen embrittlement increases with increasing carbon content [21]. Since FSW is carried out in the solid state, and therefore, solidification segregation problem of solute atoms and hydrogen uptake during melting are completely avoided. In addition, the residual stresses and distortion are significantly less compared with fusion welding processes due to the lower heat input [22]. Cui et al. [12] successfully applied FSW for joining 0.7 wt% C steel alloys without any preheating or post-weld heat treatment. Choi et al. [23] applied FSW-gas torch hybrid welding for decreasing the amount of hard martensite structure formed in the stir zone of high carbon steel alloy SK5 (0.84% C) by controlling the cooling rate during welding. Also, Chung et al. [24] successfully produced friction stir welds of SK5 high carbon steels (0.85 wt% C) below the A_1 transformation temperature with a high toughness similar to that of the base metal. In spite of these studies, the information about microstructural features; like retained austenite and tensile properties of the weld metals have not yet been examined in detail. The present study aims at investigating the microstructures and mechanical properties of

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http://dx.doi.org/10.1016/j.msea.2012.08.052

friction stir weld metals of the SK4 high carbon steel alloy (0.95 wt% C).

2. Experimental procedures

Stir-in-plate welds were performed on 2 mm thick plates of SK4 high-carbon steel using a load controlled FSW machine. The chemical composition in mass% of the steel plates is shown in Table 1. The welding tool was made of a WC-base material and composed of a 12 mm diameter shoulder and 4 mm diameter probe. The tool axis was tilted by 3° with respect to the normal direction. Argon shielding gas was used during the FSW to protect the weld zone from oxidation. The welding speed was kept constant at 100 mm/min and rotation speed varied from 100 to 400 rpm. For metallographic observations, specimens with a cross-section normal to the welding direction were cut from the stirred plates using a discharge wire cutting machine. The specimens were mechanically ground using emery papers down to2000 grade, followed by polishing using diamond paste down to 1 μm, then rinsed and degreased with acetone.

The macro- and micro-structures of various weld regions were observed using optical (OM) and scanning electron (FE-SEM) microscopes. The electron backscattered diffraction (EBSD) measurements were carried out using a JEOL JSM-7001FA field emission scanning electron microscope equipped with a TSL orientation imaging system. An X-ray diffractometer (XRD) with CoKα radiation was used to determine the volume fraction of retained austenite by comparing the relative intensities of the ferrite (α_{200}, α_{211}) and austenite (γ_{200}, γ_{220}) peaks. The hardness measurement was carried out along the cross section transverse to the welding direction with an internal spacing of 0.4 mm under a load of 2.9 N for 15 s loading time. Four lines were measured across the thickness of the steel plate to construct a hardness map. Tensile test specimens of the weld metals were machined in the transverse and longitudinal directions to the welding direction. Tests were carried out at room temperature at a strain rate of $7.5\times10^{-4}\,s^{-1}$. The fractured surfaces of the tensile tested specimens were immediately examined after the tensile test by FE-SEM.

Table 1
Chemical composition of the steel plates.

Steel type	Chemical composition (mass%)									
	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Fe
SK4	1.0	0.2	0.42	0.017	0.003	0.147	0.01	0.01	0.001	Bal.

3. Results and discussion

3.1. *Macro and microstructures of the weld metals*

The macroscopic appearance of the cross-sections transverse to the welding directions of the stirred plates at 100, 200 and 400 rpm is shown in Fig. 1. All joints are free from cracks, pores or tunnel-like defects. The FSW joints are characterized by three distinct regions: i.e., the stir zone (SZ) around the weld center line, the heat affected zone (HAZ), which is a black strip surrounding the SZ, and the non-affected base metal (BM). No clear thermo-mechanical heat affected zone was observed in these joints revealing that the material has been hardly plastically deformed. The width of the HAZ increased with the increasing rotation speed due to the increasing heat input. In addition, the etchability of the weld metal formed at 100 rpm is homogenous throughout the entire stir zone, while that formed at 200 or 400 rpm showed a different etchability contrast from top towards bottom surfaces. This variation in the macrostructural features suggests that rotation speed is an important factor affecting the type of microstructures formed in the stir zones.

The microstructure of the base metal (BM) revealed by the optical (OM) and scanning electron (SEM) microscopes is shown in Fig. 2. The microstructure consists of fine pearlite and spheroidal cementite in a ferrite matrix. The microstructure of the BM was not clearly resolved at low magnification using OM, therefore the microstructures of the weld metals are shown only at high

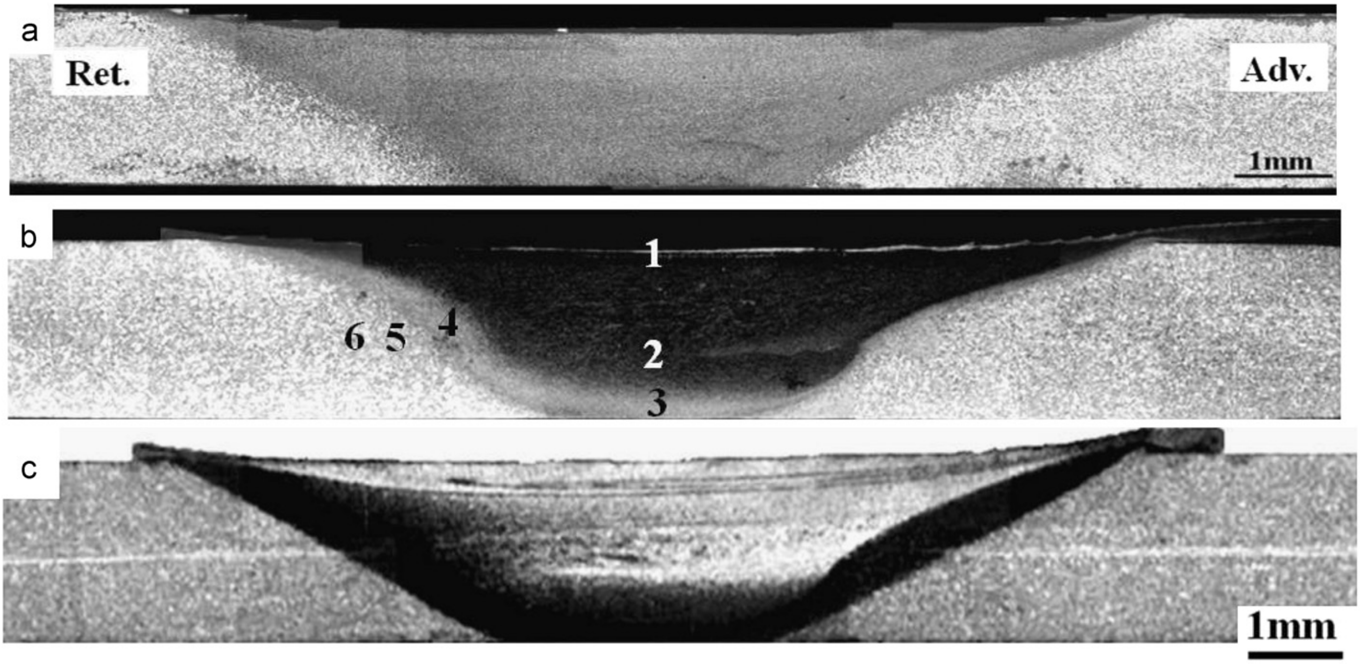

Fig. 1. Macrostructures of the cross-sections of the stirred plates at different rotation speeds: (a) 100, (b) 200 and (c) 400 rpm.