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Low temperature friction stir welding of P91 steel

Prasad Rao KALVALA [a,*], Javed AKRAM [a], Mano MISRA [a],
Damodaram RAMACHANDRAN [b], Janaki Ram GABBITA [c]

[a] University of Utah, Salt Lake City, USA
[b] SSN College of Engineering, Kalavakkam, India
[c] Indian Institute of Technology Madras, Chennai, India

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Abstract

Bead-on-plate friction stir welds were made on P91 alloy with low and high rotational speeds (100 and 1000 RPM) to study their effects on weld microstructural changes and impression creep behavior. Temperatures experienced by the stir zone were recorded at the weld tool tip. Different zones of welds were characterized for their microstructural changes, hardness and creep behavior (by impression creep tests). The results were compared with submerged arc fusion weld. Studies revealed that the stir zone temperature with 100 RPM was well below A_{c1} temperature of P91 steel while it was above A_{c3} with 1000 RPM. The results suggest that the microstructural degradation in P91 welds can be controlled by low temperature friction stir welding technique.

Keywords: Friction stir welding; P91; Low temperature; Martensite; Carbides; Impression creep

1. Introduction

Modified 9Cr-1Mo steels (P91) have been widely used for thermal power plant applications in view of their excellent creep strength. However, their weld counterparts are found to prematurely fail in their heat affected zone (HAZ) generally known as Type IV cracking [1]. Type IV cracking is found to be located in the fine grained heat affected zone (FGHAZ) and is related to the lower creep strength of the FGHAZ compared to the base material [2,3]. The degradation of martensite lath subgrains into equiaxed subgrains is regarded as one of the major factors in reducing the creep strength of the FGHAZ [4]. This is attributed to the high temperature excursion of the FGHAZ region above A_{c1}/A_{c3} during welding. Due to short dwell times at the elevated temperature, carbides will not dissolve. This results in the formation of martensite (on quenching) with lean carbon and a degraded lath subgrain structure [4]. Analytical results [5] showed that the stress triaxiality in the FGHAZ will accentuate Type IV cracking.

One of the major technical challenges is to avoid the formation of fine grains in the HAZ of P91 welds by limiting the peak temperatures in the HAZ well below A_{c1}/A_{c3} (857/914 °C) [6]. It is not possible to avoid FGHAZ in welds fabricated by conventional fusion welding processes because the melting temperatures in the fusion zone reach temperatures above 1500 °C. If the temperature in the weld metal can be controlled well below A_{c1} (857 °C), then the HAZ will not experience temperatures above A_{c1}. Such control is possible in friction stir welding (FSW) where weld temperatures and microstructural changes can be controlled. In the current investigation, experiments were conducted to control the stir zone peak temperature well below A_{c1} by controlling the weld parameters. The main emphasis of this work was mainly on the microstructural characterization, substantiated by some preliminary impression creep results. Detailed studies on impression creep studies are underway as a follow-up investigation to this work.

2. Experimental

The chemical composition (wt%) of P91 sheet used is as follows: Cr-8.91; Mo-0.98; C-0.09; Mn-0.42; Si-0.31; V-0.21; Nb-0.07; Fe-rest. Bead-on-plate friction stir welds with argon gas shielding (Fig. 1) were made on a 3 mm thick P91 steel (Normalized and tempered). The welding experiments were performed at Mega Stir Technologies LLC, Provo. A convex scrolled shoulder tool design made from a grade of

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[*] Corresponding author. Tel.: +14157228105.
E-mail addresses: jyothipr@gmail.com; prasad.kalvala@utah.edu (P.R. KALVALA).

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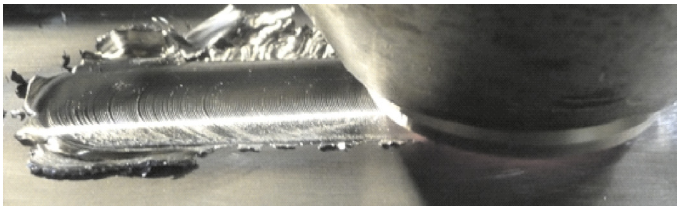

Fig. 1. Friction stir welding of P91 in progress.

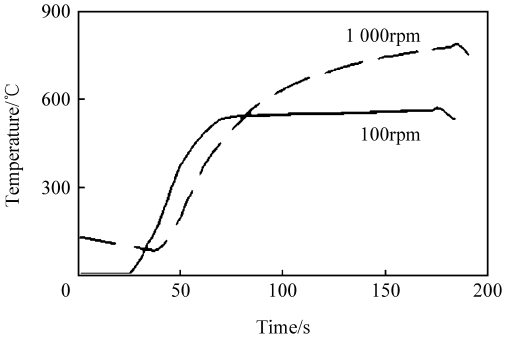

Fig. 2. Temperature profiles recorded with 100 and 1000 RPM.

polycrystalline cubic boron nitride (PCBN) weld tool was used with a small shoulder diameter and a tapered pin. The welding involved 3 stages: (1) Plunging stage: Tool rotational speed: 800 RPM; Plunge depth: 2.5 mm with tool feed rate of 76 mm/min in Z-direction. (2) Dwell stage: Plunge depth is increased from 2.5 mm to 2.8 mm in Z-direction. Once plunge depth reached 2.8 mm, the RPM was reduced to 100 from 800, the tool's dwell time (with no tool movement) was set at 5 sec with 2500 N axial force. (3) Weld stage: After 5 sec dwell time, the tool started traversing with 100 RPM, 55 mm/min traverse speed with 2500 N force. Friction stir welding experiment was repeated on a similar sheet of P91 with 1000 RPM rotational speed, keeping all other conditions same. The temperature of the stir zone was measured at the tip of the tool by inserting K-type thermocouple. For comparative purpose, a submerged arc weld (SAW) (3.75 kJ/mm heat input, post weld heat treated at 760 °C/16 hrs) was included in the study. The specimens were cut, polished and etched in the cross sectional direction of the weld to include stir (weld) zone, HAZ and base metal portions. The polished samples were etched using solution containing 1 g Picric acid + 5 mL HCl and 100 mL Ethanol. Preliminary impression creep tests were conducted to assess the relative creep behavior of different welds. Flat specimens with dimensions 20 × 10 × 3 mm were used for impression creep test with the following test conditions: Test temperature: 650 °C; Indenter: Tungsten carbide, 1 mm diameter, cylindrical, flat bottom; Punching stress: 280 MPa; Vacuum level: 10^{-3} Torr and test time: about 100 hrs (until attaining steady state). During impression creep testing, the displacement (i.e., depth of impression) was continuously monitored (at 10 minute intervals) as a function of test time. Testing was terminated after going well into the secondary creep regime.

3. Results and discussion

3.1. Temperature profiles

Typical temperatures recorded with 100 and 1000 RPM are shown in Fig. 2. It can be seen that the peak temperature at the tip of the tool was about 560 °C with 100 RPM and 775 °C with 1000 RPM. The temperature was more or less stable with welding time for 100 RPM weld whereas for 100 RPM weld, it increased gradually.

3.2. Microstructures

SEM micrographs were taken for different zones of the welds. The base metal consisted of typical martensitic lath structure with carbides distributed along grain boundaries and laths (Fig. 3). When cooled from the austenizing temperature, P91 steel exhibits a lath martensitic structure with a high dislocation density. Post weld tempering results in two kinds of precipitates: (1) $M_{23}C_6$ (M = Cr, Fe, Mo) carbides located at prior austenite grain boundaries and at other (packet, block, and martensite lath) boundaries, and (2) finely dispersed MX-type (M = V, Nb and X = C, N) carbonitrides within laths [7].

3.3. FSW weld with 100 RPM

SEM microstructure of stir zone of weld made with 100 RPM (Fig. 4(a)) showed fine grains along with fine carbides distributed in the matrix. This can help impede dislocation movement and improve creep resistance within the stir zone. As the peak temperature experienced by the stir zone was well below the A_{c1} (857 °C), it is expected that the carbides will be intact and will not dissolve into the matrix. Although $M_{23}C_6$ particles were present at the prior austenite grain boundaries in the base metal, they were found to be fragmented and uniformly distributed in the matrix due to the severe plastic deformation of friction stir welding (Fig. 4(a)). The carbide precipitates were too small to be analyzed using SEM-EDS. The tempered martensite structure was found to be preserved with lath features refined. The MX precipitates are expected to be in the matrix undissolved as their dissolution temperature is above 1250 °C

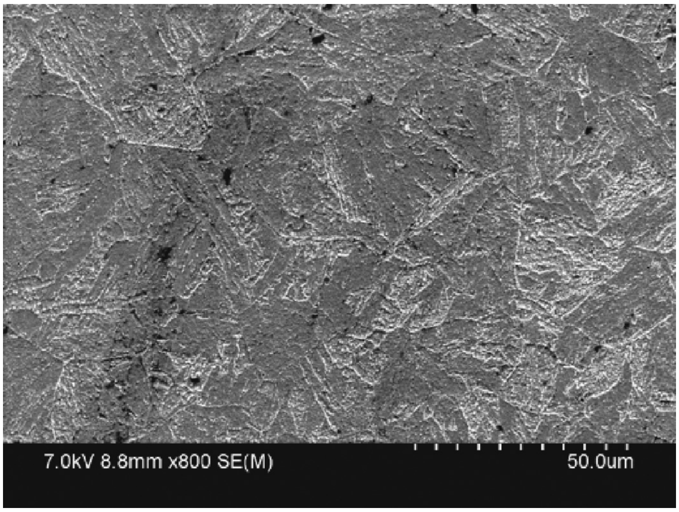

Fig. 3. Base metal microstructure.