Materials Characterization 102 (2015) 9–18

Contents lists available at ScienceDirect

Materials Characterization

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

Influence of modes of metal transfer on grain structure and direction of grain growth in low nickel austenitic stainless steel weld metals

Manidipto Mukherjee [a], Saptarshi Saha [a], Tapan Kumar Pal [a,]*, Prasanta Kanjilal [b]

[a] Metallurgical and Material Engineering Department, Jadavpur University, Kolkata, India
[b] National Test House, Saltlake, Kolkata, India

A R T I C L E   I N F O

Article history:
Received 13 September 2014
Received in revised form 3 February 2015
Accepted 5 February 2015
Available online 7 February 2015

Keywords:
Low nickel austenitic stainless steel
Mode of metal transfer
Driving forces
Electron backscattered diffraction
Grain structure
Grain growth direction

A B S T R A C T

The present study elaborately discussed the effect of different modes of metal transfer (i.e., short circuit mode, spray mode and pulse mode) on grain structure and direction of grain growth in low nickel austenitic stainless steel weld metals. Electron backscattered diffraction (EBSD) analysis was used to study the grain growth direction and grain structure in weld metals. The changes in grain structure and grain growth direction were found to be essentially varied with the weld pool shape and acting forces induced by modes of metal transfer at a constant welding speed. Short circuit mode of metal transfer owing to higher Marangoni force (M_a) and low electromagnetic force (R_m) promotes the lower weld pool volume (Γ) and higher weld pool maximum radius (r_m). Short circuit mode also shows curved and tapered columnar grain structures and the grain growth preferentially occurred in <001> direction. In contrast, spray mode of metal transfer increases the Γ and reduces the r_m values due to very high R_m and typically reveals straight and broad columnar grain structures with preferential growth direction in <111>. In the pulse mode of metal transfer relatively high M_a and R_m simultaneously increase the weld pool width and the primary penetration which might encourage relatively complex grain growth directions in the weld pool and cause a shift of major intensity from <001> to <111> direction. It can also be concluded that the fusion zone grain structure and direction of grain growth are solely dependent on modes of metal transfer and remain constant for a particular mode of metal transfer irrespective of filler wire used.

1. Introduction

Ni is the alloying element traditionally used in stainless steels to stabilize the face-centered-cubic (*fcc*) crystal structure at room temperature. Due to the price evolution of nickel in recent years, the chromium-high manganese (5–9% Mn) stainless steels with a low nickel (<2%) content and complementary nitrogen additions have been considered as the potential substitution for the common Cr–Ni Type 300 series austenitic stainless steels [1,2]. The substitution of Ni by Mn and N is an interesting proposition, both from an economical as well as an engineering point of view. Although Mn can be regarded as an austenite stabilizer, the addition of Mn alone is not sufficient to stabilize the austenite phase at room temperature [3], especially in the presence of Cr which is a strong ferrite stabilizer [4]. The addition of Mn, nevertheless, is effective in increasing the solubility of N in the liquid steel and the fraction of austenite formed during solidification. Low nickel austenitic stainless steel (LNiASS) also possesses higher strength and ductility compared to 300 series austenitic stainless steels because of more effective solid-solution strengthening and strong austenite stability which reduces the tendency to form ferrite and deformation-induced α' and ε martensites [5–7]. Therefore, high potential low nickel austenitic stainless steels (LNiASSs) can be utilized in industrial applications which include the power-generating industry, ship building, railways, cryogenic processes, chemical equipment, pressure vessels, petroleum and nuclear industries [8].

Welding is the most common method of fabrication even for stainless steel structures in different applications [9]. Among the various welding techniques, gas metal arc welding (GMAW) process is now the most reliable, cost-effective, techno-economic and widely practiced method in most industries due to its high productivity, relative cleanliness, ability of welding complicated shapes with large and small dimensions and availability of a wide range of materials [10]. However, one of the important characteristics of GMAW process is it could be carried out with different modes of metal transfer such as short circuit, globular, spray [11] and pulse [12]. Early investigation has shown that different modes of metal transfer significantly alter the heat and fluid flow phenomena in the melt and affect the weld pool geometry [12–14] which considerably influences the solidification structure, grain growth, phase transformation, texture and other microstructural constituents of the weld produced. Understanding the grain structure and grain growth behavior of the fusion zone during welding is still evolving due to its strong influence on weld metal properties as well as development of advanced characterization tool such as electron backscattered

---

* Corresponding author.
E-mail address: tkpal.ju@gmail.com (T.K. Pal).

http://dx.doi.org/10.1016/j.matchar.2015.02.006
1044-5803/

diffraction (EBSD) technique. At present few studies are available on the EBSD analysis of welded joints of standard austenitic stainless steel (ASS), ferritic stainless steel (FSS) and duplex stainless steel (DSS) [15–17]. Cho et al. [16] have examined the defect-free friction stir welded (FSW) joints of 409 FSS where a remarkably fine-grained microstructure in stir zone (SZ) was developed by dynamic recrystallization which eventually increased the hardness. The degree of grain fineness and increased hardness was markedly correlated with the higher fraction of low angle grain boundary (LAGB) and the shear texture (in bcc materials) in the SZ. Presently, the FSW process has got considerable attention in texture analysis due to solid state nature of the FSW process which involves pressure, friction and plastic deformation. Even texture analysis was performed in fusion welding where plastic deformation is absent during operation. Bouche et al. [15] investigated the crystallographic texture of 316L GTA weldments in fast breeder reactors on the basis of a multiscale approach and found that the ferrite dendrites ($\{1\ 0\ 0\}_{\delta}$) were nearly parallel to the neighboring austenite columnar grains ($\{1\ 0\ 0\}_{\gamma}$) at the same fiber texture. Furthermore, Badji et al. [17] have recently investigated the crystallographic texture and anisotropic properties in a 2205 DSS after gas tungsten arc welding and subsequent annealing heat treatment. They have concluded that the welding operation significantly affects the microstructural modifications in the texture of the fusion zone compared to the deformation and recrystallization textures of the base metal. It was also observed that subsequent annealing heat treatment at different temperatures either produced homogeneous or heterogeneous anisotropic behavior of the weldments. Available literatures mostly dealt with the anisotropic behavior of weldments related to texture after welding of standard alloys. However, the implication of fusion zone grain structure is that the anisotropic behavior and the mechanical properties of the weld metals are severely affected. Furthermore, the fusion zone grain structure is dependent on the type and shape of weld pool which is controlled by the mode of metal transfer [13]. Thus understanding the correlation between modes of metal transfer and grain structure of the fusion zone would be very useful to control weld metals' final properties [11].

In fusion welding process the partly melted base metal grains (HAZ grains) at the fusion boundary, in general, act as seed crystals for the growing columnar grains [18]. The columnar grains having their preferred growth direction parallel to the maximum temperature gradient in the melt generally outgrow those grains that do not have the favorable orientation. Competitive growth during the initial stage of the solidification process leads to an alignment of the crystals in the heat flow direction [19]. However, due to shift in the direction of the maximum temperature gradient in the weld pool, the growth direction of the columnar grains will change continuously from the fusion line towards the center of the weld and may result in curvature of the columnar grains [20]. Nevertheless, the maximum temperature gradient in the weld pool will fluctuate with the variation in modes of metal transfer which strongly influence the weld pool shape and control the growth direction, grain structure, texture and properties of the weld metal. However, there is practically no information available in literature on the link between different modes of metal transfer, grain structure and direction of grain growth in the LNiASS weld metals using EBSD technique.

The present study describes in detail the effect of modes of metal transfer on fluid flow mechanism, weld pool shape, grain structure and direction of grain growth in the weld metals of LNiASS. The weld metals were prepared by varying three modes of metal transfer namely short circuit mode (SC-mode), spray mode (S-mode) and pulse mode (P-mode) using AISI 308L and AISI 316L austenitic filler wires at constant welding speed. The overall purpose of this study is to investigate the effect of different modes of metal transfer on:

a. Weld pool shape, driving forces and fluid flow behavior using mathematical calculations (driving forces and Rosenthal thin plate solution of pseudo-steady state temperature distribution) and macrographs.

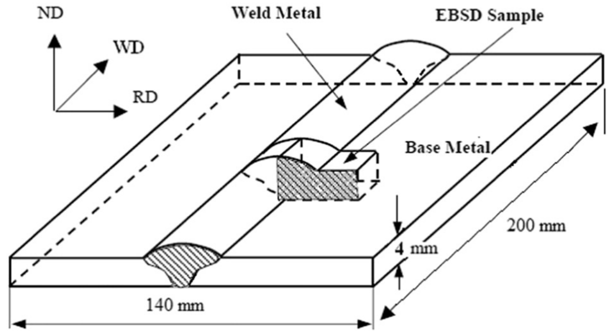

Fig. 1. Weld preparation and test plate assembly.

b. Micro-texture evolution (grain structure and direction of grain growth) at the fusion zone of LNiASS by measuring the orientation data from EBSD.

The present study will provide clear insight on two major subjects, i.e., 1) whether the weld pool shape, grain structure and direction of grain growth are solely dependent on the modes of metal transfer at a constant welding speed, or not; and 2) whether for a particular mode of metal transfer the grain structure and direction of grain growth will remain constant irrespective of filler wire used in LNiASS weld metals.

2. Experimental

2.1. Materials

A comparatively new class of low nickel austenitic stainless steel (LNiASS) designated as LN1 manufactured by Salem Steel Plant, Steel Authority of India Ltd., Tamil Nadu is used in the experiment. The hot rolled sheets of 4 mm thickness were cut into the required dimension (200 mm × 70 mm × 4 mm). Details of weld joint preparation and test plate assembly for the GMA welding process are shown in Fig. 1. The chemical compositions of the base metal and two austenitic filler metals (i.e., AISI 308L and AISI 316L) of size 1.2 mm diameter are given in Table 1.

2.2. Welding procedure

The experiments were conducted using a KEMPPI, Finland make water Cooled Universal MIG/MAG machine (Model: FastMIG Pulse 450) using DC electrode positive (DCEP). The welding conditions and process parameters that were used to fabricate the joints are given in Table 2. The initial joint configuration was obtained by securing the plates in flat position using tack welding. Square butt joints with a root gap of 1.5 mm were fabricated using the selected GMAW process parameters so the short circuit (SC), spray (S) and pulse (P) modes of metal transfer could be operated. Details of pulse parameters used in this study are given in Table 3. To ascertain the operating mode, current and voltage were recorded by an oscilloscope during each welding run. An example of oscilloscope reading for short circuit mode, spray mode and pulse spray mode of metal transfer is shown in Fig. 2. The welding operations were performed using Ar + 10% CO_2 shielding gas mixture at constant welding speed of 8.34 $mm \cdot s^{-1}$. All necessary care was taken to avoid joint distortion by applying clamping devices. The soundness of all the welded plates was examined using radiography testing.

2.3. Electron backscattered diffraction (EBSD) analysis

The welded samples for EBSD analysis were sectioned perpendicular to the welding direction as shown in Fig. 1. In order to maintain consistency with the terminology typically used for the GMAW process, the