Materials Science & Engineering A 719 (2018) 82–92

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

On the microstructure evolution in friction stir processed 2507 super duplex stainless steel and its effect on tensile behaviour at ambient and elevated temperatures

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ARTICLE INFO

Keywords:
Super duplex stainless steel
Friction stir processing
Grain size
Superplasticity

ABSTRACT

The microstructures and mechanical properties of friction stir processed 2507 super duplex stainless steel were examined. Experimental results revealed that there is an optimum traverse speed for a given rotational speed that gives minimum grain size. The individual and synergistic effects of FSP parameters such as heat input, strain rate and strain on the grain size of the material were evaluated. The results indicate that counteracting effect of heat input and the combined effect of strain rate and strain results in achieving minimum grain size at an intermediate traverse to rotation speed ratio. The twin boundaries (particularly Σ3 CSL boundaries) in the stir zone of friction stir processed material reduced considerably compared to that in the base material. Both the base material and the friction stir processed material with the smallest grain size achieved were subjected to tensile testing at ambient and elevated temperatures under different strain rates. The results obtained are presented and discussed here.

1. Introduction

In recent years, friction stir processing (FSP), a method of severe plastic deformation (SPD) is widely used to impart homogeneous grain refinement. In this technique, an axially loaded rotating tool with specially designed pin is inserted into the work piece and traversed along the area of interest. During this interaction of rotating tool and work piece, heat is generated due to friction and the material undergoes severe plastic deformation resulting in fine grain size. In spite of the advancement of instrumentation, equipment and tool material, the FSP of materials such as steel, titanium, and nickel base-alloys and its application on industrial scale is still a challenge to researchers. The main challenge is the availability of tool materials which can withstand extreme conditions of load and temperature, particularly for welding of thicker metal plates. Further, a clear understanding of the individual and synergistic effects of FSP processing parameters is imperative in obtaining the desired microstructure and defect free material. Though various tools made out of refractory materials such as W-Re, polycrystalline boron nitride (PCBN) and WC [1] have been used for processing different materials, controlling the deformation zone microstructure and obtaining a defect free material has not been investigated extensively.

The microstructure evolution and the resulting mechanical properties of FSP samples are affected by different process parameters such as (a) tool rotation speed, (b) geometry of tool, (c) tool tilt angle, (d) traverse speed, and (f) axial force. Among these parameters, tool rotation speed and traverse speed are the most important parameter as they strongly influence the heat input to the material. Saeid et al. [2] studied the effect of welding speed in the range of 50–250 mm/min at constant rotational speed of 600 rpm on the microstructure and mechanical properties of a 2 mm thick SAF 2205 duplex stainless steel (DSS). They reported that during friction stir welding (FSW) the grain size of both ferrite and austenite decreased with increasing welding speed up to 200 mm/min, but a groove like defect was observed at higher welding speed of 250 mm/min due to insufficient heat input. It has been well established that refinement in the grain size of 2507 super duplex stainless steel (SDSS) occurs during FSP/FSW by nucleation of dynamically recrystallized grains [3]. After the formation of new grains during FSP, they may experience static grain growth due to the thermal effect during cooling. The dependence of grain size on temperature and time is given by Eq. (1), as reported by Sato et al. [4]

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https://doi.org/10.1016/j.msea.2018.02.032
Received 20 November 2017; Received in revised form 29 January 2018; Accepted 7 February 2018
Available online 08 February 2018
0921-5093/

$$\ln D = -\frac{Q}{2RT} + \frac{\ln(At)}{2} \quad (1)$$

where, D is the final recrystallized grain size, Q is the activation energy for grain growth, T is the absolute temperature, A is a constant, R is the ideal gas constant, and t is the time. According to Eq. (1) the final recrystallized grain size will be smaller if values of temperature (T) and time (t) are reduced. Therefore, it is important to control the thermal effects during FSP i.e., the peak temperature obtained during the processing stage and cooling rate thereafter to get the desired microstructures. In this regard, attempts were made to carry out FSP under water to enhance the cooling rate and thereby achieve finer grain size and better mechanical properties compared to that obtained during normal or conventional FSP [5]. For a given tool geometry and depth of penetration, the peak temperature can be varied by changing the rotation speed (ω) or the traverse speed (V) and is expressed as follows [6];

$$\frac{T_P}{T_m} = K\left(\frac{\omega^2}{V.\,10^4}\right)^{\alpha} \quad (2)$$

where, T_P is peak temperature, T_m is melting point, K and α are constants. It can be inferred from Eq. (2) that with increasing rotation speed or decreasing traverse speed, the maximum or peak temperature attained in the material increases. Hao et al. [7] investigated the influence of tool rotation speed and welding or traverse speed on Al-Mg-Er alloy and reported that the stir zone (SZ) grain size increased with increasing tool rotation rate or decreasing traverse speed. Sarlak et al. [8] investigated the evolution of microstructure in a lean DSS by varying the traverse speed (from 50 to 150 mm/min) during FSW and reported continuous refinement of grain size with increasing traverse speed and concurrent improvement in the corrosion resistance of SZ. Cavaliere et al. [9] reported that the grain size decreased initially with increasing the traverse speed from 40 to 165 mm/min and thereafter reached plateau with no further variation in grain size as the speed was increased to 460 mm/min during FSP of 6068 Al alloy. Mosallae and Dehghan [10] observed that at constant rotation speed (720 rpm), increasing traverse speed from 10 to 20 mm/min decreased the SZ grain size from 21.0 ± 0.9 μm to 13.0 ± 0.6 μm and thereafter, the SZ grain size increased from 13.0 ± 0.6 μm to 18.0 ± 1.3 μm with further increasing of traverse speed from 20 to 30 mm/min during FSP of Al-1100 Alloy. Patel et al. [11] reported that the initial grain refinement observed in Al-Zn-Mg-Cu alloy during FSP is due to the reduced heat input to the material as the traverse speed was increased from 31 to 50 mm/min. Further, they attributed the increase in grain size with increasing traverse speed (50–78 mm/min) to the lack of heat generation during processing. A recent study on multi-pass FSP of 2507 super duplex stainless steel reports increased grain refinement with increasing number of passes [12]. The existing literature contains non-uniformity over microstructure evolution and its relationship with the processing parameters. Therefore, in this article microstructural evolution during FSP as a function of processing parameter is thoroughly investigated.

Materials with such very fine grains produced through various severe plastic deformation processes are expected to exhibit superplasticity wherein the material possesses high tensile ductility under suitable test condition. This superplastic behaviour is characterized using the Mukherjee-Bird-Dorn constitutive equation [13];

$$\dot{\varepsilon} = \frac{ADGb}{kT}\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{n} \quad (3)$$

where, $\dot{\varepsilon}$ is the strain rate, A is a dimensionless constant, G is the shear modulus, b is the magnitude of Burgers vector, k is the Boltzmann constant, T is the absolute temperature, d is the grain size, σ is the applied stress, D is the diffusion coefficient, n ($= 1/m$) and p are termed as stress exponent and inverse grain size exponent respectively. Superplasticity is often associated with high values of strain rate sensitivity (m) and the value of m is generally greater than 0.3. Due to the presence of dual phase (ferrite and austenite) in the DSS, they exhibit better superplastic performance compared to their single phase counterparts such as ferritic and/or austenitic stainless steels. It has been reported that α/γ interphase boundary sliding is faster by a factor of 10^2 to 10^3 than α/α and γ/γ grain boundary sliding in DSS [14]. Jiménez et al. [15] reported low values of n ($= 1/m$), 2–3, in the temperature range of 850–1100 °C for strain rates up to 10^{-3} s^{-1} and suggested that the rate controlling deformation mechanism to be the grain boundary sliding (GBS). Wang et al. [16] examined high temperature ductility of FSP samples of 7075 Al alloy and reported 3250% maximum elongation at 535 °C and strain rate of 10^{-2} s^{-1}. It has been understood that to achieve superplastic deformation characteristics, the basic requirement of fine grain size is necessary but it is not always sufficient condition. If the fine grain microstructure is not stable at high temperature, superplastic elongation will be significantly reduced [6]. Charit et al. [17] observed reduced ductility at 510 °C, in FSP samples (SZ of single and multiple pass) compared to parent material (7475 aluminium alloy) due to abnormal grain growth in the former. Although, some studies have been reported on the effect of FSP on superplastic properties of different materials, an investigation on FSP samples of DSS has not been reported.

Therefore in the view of limited studies reported in the literature on microstructure evolution during FSP and its effect on tensile properties, the aim of the present work is two-fold. First objective is to systematically investigate the microstructural evolution during FSP as a function of processing parameter and thereby address the contradictions existing in the literature. The second objective is to investigate the room and elevated temperature tensile behaviour of the base material (BM) and material processed under optimum conditions of FSP.

2. Experimental procedures

2.1. Material and FSP

Super duplex stainless steel (SDSS) of grade 2507 was procured in the form of 8 mm thick sheet with its nominal composition given in Table 1. From the as-received material samples of dimensions 400 mm in length and 300 mm in width were prepared and subjected to FSP using a 100 kN FSW machine. Lanthanated tungsten (W-1La_2O_3) tool with a shoulder diameter, pin length, and pin diameter of 25, 6, and 10 mm respectively was used for the study. The tool tilt angle (angle between the tool axis and the vertical) was maintained at zero degree during the processing. In order to avoid the oxidation of the surface, Ar - gas shielding was used around the tool. FSP was conducted with a constant tool rotation speed of 800 rpm with a varying traverse speed of 10, 25, 50, 100, 150, and 175 mm/min. For simplicity, the sample processed at 800 rpm and traverse speed of 10 mm/min, 25 mm/min, 50 mm/min, 100 mm/min, 150 mm/min, and 175 mm/min are designated as FSP10, FSP25, FSP50, FSP100, FSP150, and FSP175 respectively. The Z-axis force during the processing was maintained at constant value of 9 kN

Table 1
Nominal chemical composition of 2507 SDSS.

Elements	C	S	P	Mn	Si	Cr	Ni	Mo	Cu	N	Fe
Wt%	0.016	0.003	0.023	0.72	0.25	25.20	6.9	3.79	0.19	0.26	Rest