

Effects of Friction Stir Processing on the Microstructure and Mechanical Properties of Fusion Welded 304L Stainless Steel

C.J. Sterling¹, T.W. Nelson¹, C.D. Sorensen¹ and M. Posada²

¹Department of Mechanical Engineering
Brigham Young University
435 CTB

Provo, UT, 84602, USA

²Naval Surface Warfare Center Carderock Division
Welding & NDE Branch
95 MacAurtur Blvd
West Bethesda, MD 20817, USA

Keywords: Friction Stir Welding; Friction Stir Processing; Microstructure; Stainless Steel; Parameter Studies; Welding; Microstructure Modification

Abstract

A variation of FSW, friction stir processing (FSP), has been used to modify selected regions of materials to enhance specific properties while eliminating fusion welding defects such as porosity, cracking, and the cast microstructure. The combination of fusion welding defects and high tensile residual stresses caused by the solidification of the molten weld pool adversely affect the post weld service integrity. FSP has been demonstrated to eliminate many of these problems while at the same time improving the resulting properties. FSP has been utilized to locally process regions of arc weldments in 304L stainless steel to improve the service integrity. The cast microstructure and coarse delta-ferrite is replaced with a fine-grained wrought microstructure. This paper presents a preliminary processing window for FSP of 304L stainless steel, the resulting microstructure associated with this process window, along with considerations given to mechanical properties and corrosion.

Introduction and Background

Friction stir welding (FSW), since its conception by TWI in 1991[1,2], has been used extensively and successfully in joining aluminum and other low-temperature materials. FSW is a solid-state joining process in which the material is softened and plasticised by a rotating tool consisting of a shoulder and a smaller concentric pin. The pin tool acts to transport material from the front to the back of the tool where the shoulder provides the forging pressure necessary to reconsolidate the material forming a weld. The rotating tool is translated along the weld joint leaving a homogeneous, refined grain size, wrought microstructure. The resulting joint is superior to that of a traditional arc weld in that it has lower residual stresses, and is free of the cast microstructure and defects such as cracking and porosity.

A variation of FSW called friction stir processing (FSP), which uses the same tooling, has been proven effective in selectively modifying the microstructure of specific areas to improve local properties [3]. Both processes have been shown to be superior to

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2004		2. REPORT TYPE		3. DATES COVERED 00-00-2004 to 00-00-2004	
4. TITLE AND SUBTITLE Effects of Friction Stir Processing on the Microstructure and Mechanical Properties of Fusion Welded 304L Stainless Steel				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center Carderock Division, Welding & NDE Branch, 95 MacAurtur Blvd, West Bethesda, MD, 20817				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

traditional arc welding in many ways. Until recently however, FSW and FSP use has been limited to low-temperature materials.

A new tool material developed at Brigham Young University¹ has made it feasible to join or process high-temperature materials via FSW/P [4,5]. Success has been achieved in FSW austenitic and super austenitic stainless steels, nickel based alloys, low-carbon steels, and high strength-low alloy steels with this new tool material. While the benefits of FSW high-temperature materials are not fully understood at this time, many of the benefits achieved in low-temperature materials have been observed in high temperature materials. In addition, significant reductions in harmful fumes have been observed in FSW/P of austenitic stainless steels. The levels of hexavalent chromium were reduced to the point that they were not detectable by a standard method [6].

It is the ongoing objective of this investigation to establish a process window for FSP of 304L stainless steel that would later be implemented to FSP of fusion welds. Similarly, FSP would be utilized to improve properties and service integrity of arc-welded structures.

Experimental

The base material selected for this investigation was 304L stainless steel with nominal composition in weight percent of 0.03C max, 2.0 Mn, 0.75 Si, 8.0-12.0 Ni, 18.0-20.0 Cr, 0.1 N, 0.03 S, 0.045 P, and the balance Fe. This material was procured as 6 mm (0.25") thick sheet that was cut into sections 8 by 24 inches for processing. The oxide was removed prior to processing and the plates were secured to a flat anvil. The FSP machine used custom designed and built CNC machine producing 30 horsepower.

The tool material used was polycrystalline cubic boron nitride (PCBN). The tool had a 15 mm (0.6") inch diameter shoulder with a pin length of 2 mm (0.08"). Due to the high temperatures encountered, a liquid-cooled tool holder produced by Tecnara was used to minimize heating of spindle bearings. Ethylene glycol refrigerated in a commercial recirculating cooler was passed through the tool holder at a temperature of 15 °C.

Processing began with a spindle speed of 800 RPM and travel rate of 50 mm/min. The travel was incremented by one inch every 150 mm for a final travel of 130 mm/min. In a like manner the spindle speed was incremented by 100 RPM each pass for a final speed of 1200 RPM and 130 mm/min. Plates were sectioned and polished for optical metallography. The sections were final polished with 3 µm diamond paste and electrolytically etched with a solution of 10 grams oxalic acid in 100 ml distilled water for 45-60 seconds at 10 volts.

Results and Discussion

In this initial study the authors have applied FSP to fusion welds in order to eliminate some of the problems typically associated with arc welding. Autogenous arc welds were

¹PCBN tooling was developed in cooperation with Advanced Metal Products (Scott Packer) and Smith MegaDiamond Inc.

performed in 316L stainless steel and subsequently processed at the weld toes via FSP. The results (Figure 1) were very promising.

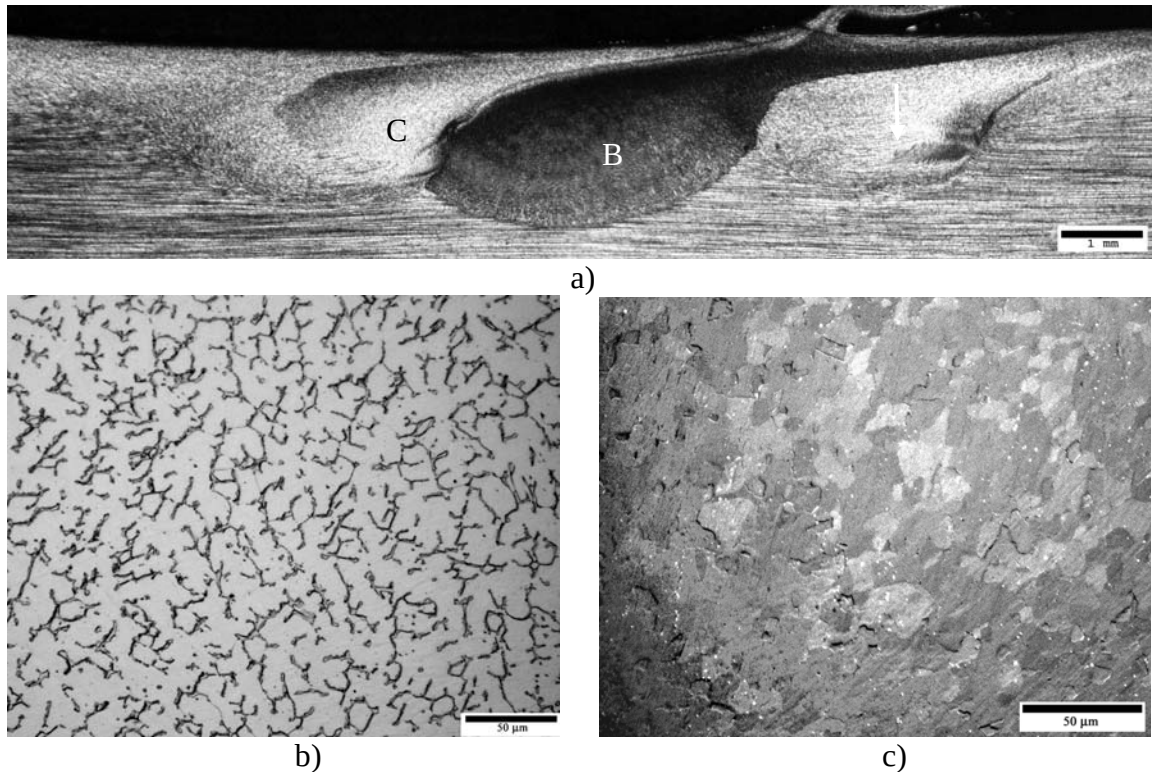


Figure 1. Photomicrographs of FSP 316 arc weld a) photomacrograph showing arc weld and FSP at weld toes b) microstructure autogenous arc weld showing a typical austenite with skeletal ferrite microstructure c) fine grained wrought microstructure associated with DXZ of FSP zone.

The dark region in the center of Figure 1a is the arc weld. This microstructure shows the typical cast weld microstructure which consists of austenite with 15-20% retained ferrite as shown in Figure 1b. Although the ferrite present has been shown to be beneficial with regards to liquation related cracking, it can be detrimental to corrosion and mechanical properties. In contrast, at the weld toes, where FSP was performed, the volume percent second phase is greatly reduced as observed in Figure 1c. Further observations also showed that the second phase present consisted of small spherical particles. It is likely that the finely distributed spherical particles would exhibit an improvement over the long ferrite stringers associated with the arc weld microstructure with respect to properties.

A preliminary process window for FSP of 304L stainless steel was investigated. This window has proven to be larger than initially thought feasible. The preliminary process window for FSW of 304L stainless steel is presented in Table 1, “Good” indicates that the processing was fully consolidated; “Poor” indicates a lack of consolidation (LOC). Investigations to explore the extent of this window are on going. Future analysis of this window will incorporate both temperature and process load data to develop an increased understanding of the processing window as well as providing additional variables to refine the process.

Table 1. Processing window for 304L stainless steel.

1100	Good	Good	Good	Good
1000	Poor	Good	Good	Good
900	Poor	Poor	Good	Good
800	Good	Good	Tool Broke	NA
RPM	50	75	100	130
MM/MIN				

The FS processed regions in 304L were typical of those seen in FSW of aluminum, and other steels. The processed zone consists of a nugget region or DXZ, a TMAZ, and a HAZ. These are shown in the representative transverse photomicrograph in Figure 2.



Figure 2. Typical FSP zone, shown from section processed at 800 RPM and 50 mm/min.

While the processed region was free of defects over a wide range of process parameters, the resulting microstructures exhibited distinct difference for different combinations. Most parameter combinations produced a microstructure similar to that shown in Figure 2 with a concentration of second phase present at the lower advancing side of the processed zone (indicated by the arrow). While initial indications were that this second phase was delta-ferrite, recent work by Okamoto *et. al.* has suggested that this second phase is actually sigma [7].

Subsequent testing and evaluation has revealed that the density of this second phase can be altered with different process parameters (Figure 3). It was observed that processing at 1000 RPM and 100 mm/min produces a better microstructure with a lower density second phase. It is likely that the lower volume percent second phase regions will exhibit better corrosion properties as well as increased fatigue properties over a similar zone with a higher volume percentage.

While the authors are confident that a good processing window has been found for FSP 304L base material, this window must be tested for FSP of arc welds to see if it is translatable to a situation where a large amount of ferrite is already present.

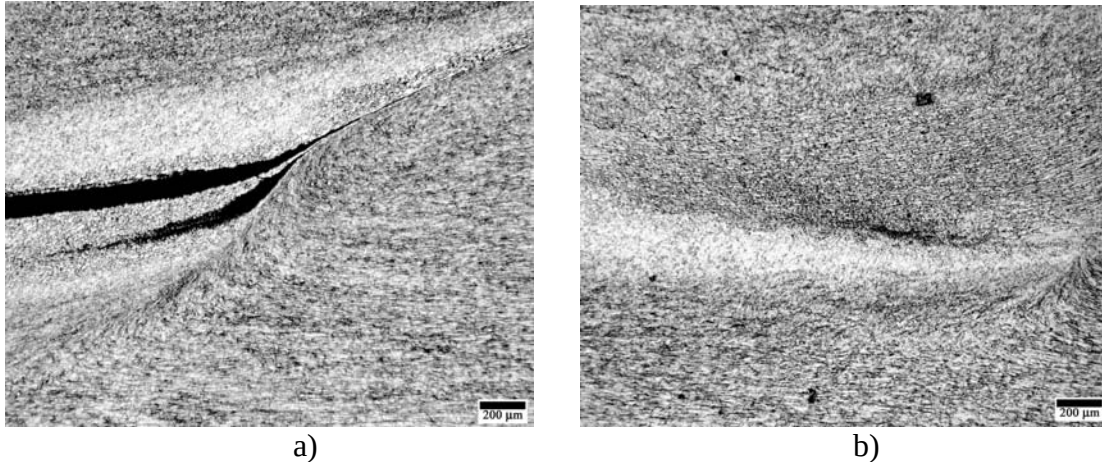


Figure 3. Differences in the ferrite concentrations at the advancing side of the tool. Processed at a) 800 RPM and 50 mm/min and b) 1000 RPM and 100 mm/min.

Conclusions

From this investigation, the following conclusions may be drawn:

1. FSP is a viable method for altering the microstructure of 304L stainless steel.
2. A well-defined processing window for 304L has been found.
3. Spindle speed and travel affect the final microstructure of FSP 304L.
4. PCBN tooling exhibits little or no wear when correct parameters are utilized during FSP 304L stainless steel.

Acknowledgements

The authors wish to acknowledge DARPA contract No. MDA972-02-C-0030, which provided financial support for this study.

References

- [1] TWI; W.M. Thomas, E.D. Nicholas, J.C. Needham, P. Temple-Smith, S. Kallee, WKW; C.J. Dawes, UK Patent Application 2 306 366 A, Filed: 17 Oct.1996 (UK 9521570, 20 Oct.1995; 9523827, 22 Nov.1995; 9605864, 20 Mar.1996).
- [2] The Welding Institute; W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, and C.J. Dawes, PCT World Patent Application WO 93/10935.
- [3] M. Mahoney et al, "High Strain Rate, Thick Section Superplasticity Created Via Friction Stir Processing," Proceedings of Symposium sponsored by the Shaping and Forming Committee of the Materials Processing & Manufacturing Division (MPMD) of TMS, Indianapolis, Indiana Nov. 2001.
- [4] C.D. Sorensen, T.W. Nelson and S. Packer, "Tool Material Testing for FSW of High-Temperature Alloys," 3rd International Symposium of Friction Stir Welding, Kobe, Japan, Sept. 2001.

- [5] T.W. Nelson, C. D. Sorenson, S. Packer, "Friction Stir Welding of High Temperature Materials", Proceedings of the 6th International Conference on Trends in Welding Research, Pine Mountain, GA, April 2002.
- [6] Personal communication with Murray Mahoney, Rockwell Scientific.
- [7] Okamoto et al, "Metallurgical and Mechanical Properties of Friction Stir Welded Stainless Steels," To be presented at the 4th International Symposium on Friction Stir Welding, Park City, UT, May 2003.