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Prediction of Friction Stir Welding Defect-Free Joints of AISI 304 Austenitic Stainless Steel Through Axial Force Profile Understanding

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Friction Stir Welding (FSW) joints of AISI 304 austenitic stainless steel (304 SS) using position controlled mode were investigated in order to understand and relate axial force behavior to welding quality. Joints were produced using two tools and four combinations of specific parameters. The results showed coherence between the axial force profiles and the low-magnification overviews of the welded joints. For defect-free joints, only a natural oscillation on axial force occurred after tool plunge. In contrast, abnormal or abrupt oscillations were directly associated with common welding defects, such as voids and nugget collapse.

Keywords: *friction stir welding, AISI 304 stainless steel, axial force, welding defect*

1. Introduction

Friction Stir Welding (FSW) is a solid-state welding technique that has emerged as one of the most important joining processes with a vast application potential in aerospace, automotive and shipbuilding industries[1,2]. Its basic concept is remarkably simple. In FSW, a non-consumable rotating tool is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint[2]. The FSW tool consists of a pin and a shoulder. The pin is designed to disrupt the faying surfaces of the workpiece, shear material in front of the tool, and move material behind the tool. The shoulder is needed to generate sufficient heat, allowing material flow around the tool. Figure 1 shows a schematic illustration of the FSW process. Considering its potential, the weld formation mechanisms associated with FSW must be clearly understood, especially the axial force behavior during FSW. Without an adequate axial force acting through the tool, the forging of the plastically deformed material would not occur properly and voids would form[2].

Several researches on FSW have already examined the effect of two major weld parameters - rotation speed (RS) and transverse speed (TS) - to justify the quality of the welds. Meran et al.[3] conducted a study of AISI 304 austenitic stainless steel, at a tool rotation speed of 1000 rpm and welding speeds of 40-100 mm per min. They found that defect-free FSW were produced under a wide range of welding speeds. Reynolds et al.[4] conducted a similar study using AISI 304L austenitic stainless steel at two rotational speeds, 300 rpm and 500 rpm, and welding speed of 100 mm per min. Sound welds were obtained for both combinations of parameters, however, the 300 rpm weld exhibited higher strength than the 500 rpm.

Typically, rotation speed and traverse speed are independently controlled. However, when plunge depth is also independently controlled, the axial force becomes a function of the other three parameters[5]. In that case, when RS, TS and PD are kept constant, abnormal or abrupt axial force oscillations can be associated with the loss of material in the nugget , leading to the formation of volumetric defects. Therefore, the purpose of this work is to confirm the possibility of predicting FSW defect-free joints of 304 SS, by analyzing and understanding axial force profiles, whilst other parameters are independently controlled and kept constant.

2. Experimental Procedure

Plates of 304 SS with thickness of 2.5 mm were friction-stir welded in butt joint configuration, using a MTS three-axis gantry system. Table 1 shows the experimental chemical composition of the as-received material. The plates were reduced to rectangular specimens of 100 mm × 150 mm. In order to prevent the surface oxidation, argon shielding gas was employed around the tool at a flow rate of 20 L/min. To produce the welds, a Polycrystalline Cubic Boron Nitride (PCBN) tool (with a shoulder and a cylindrical pin of 15 mm and 10 mm in diameter, respectively) and a W-25%Re tool (with a shoulder and a 45° conical pin of 13 mm and 6 mm in diameter, respectively) were utilized.

The specific combinations of parameters and tools presented in Table 2, based on preliminary research, were investigated. The process was operated in a position-controlled mode, so that axial force varied to maintain plunge depth in 2.4 mm. The tilt angle of the tool was kept constant at 0° during the welding process.

Transverse weld cross-sections were cut by electrical discharge machining for metallographic analysis in the positions of interest. After metallographic preparation, the samples were electrolytically etched in a solution of 10% oxalic acid and 90% distilled water with a power supply set at 19 V, during 18 s. Microstructure was observed by optical microscopy for the cross-sections of the joints.

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Table 1. Chemical composition of 304 SS sheets.

Element	Fe	Cr	Ni	Mn	Si	C	N	P
wt.%	Bal.	18.40	8.15	1.60	0.42	0.08	0.05	0.03

Table 2. Parameters specifications.

Join specification	Tool	Rotational speed (rpm)	Welding speed (mm/s)	Plunge depth (mm)
SS-PCBN-500	PCBN	500	2	2.4
SS-PCBN-800	PCBN	800	2	2.4
SS-WRe-400	W-25%Re	400	2	2.4
SS-WRe-600	W-25%Re	600	2	2.4

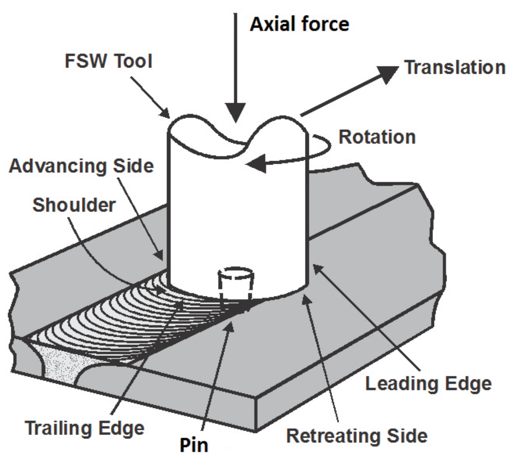

Figure 1. Schematic drawing of friction stir welding.

3. Results and Discussion

3.1. Axial force profile – defect-free joints

Figure 2 shows axial force versus time curves, during FSW process for defect-free joints. Both curves exhibit a similar behavior. At the beginning, when the tool plunges deeper into the material, metal has to be displaced from underneath the tool. In order for the metal to flow out from underneath the tool, it has to overcome the restraining forces of the die cavity. Thus, sufficient pressure gradient has to be developed along the metal flow path. The channel of metal begins underneath the pin and flows outward and upward to the edges of the shoulder. When the tool is not plunging, the pressure along this channel is in equilibrium, therefore, no metal is displaced. However, when the tool starts to plunge downwards, a large pressure gradient begins to build up on the metal along this channel. This pressure increase is balanced by an increase in axial force. The pressure is greatest underneath the pin, but as the flow channel gets further away from the pin bottom and closer to the surface, it decreases. At the outer edge of the shoulder, the pressure naturally becomes zero because the metal no longer has to flow out from underneath the tool. Once the metal is displaced and the tool reaches its new plunge depth, the pressure gradient returns to a steadystate equilibrium. From this point on, an oscillation of axial force and corresponding pressure underneath the tool would just occur if the radius and volume of rotating metal oscillated. In the case of any material loss, a weld nugget free of voids cannot be formed and the materials cannot be reliably joined. Nevertheless, only natural oscillations - theorized based on the coupling between shear flow stress, deformation, axial pressure and temperature - were observed in both curves, being the first indicative of defect-free joints.

Figure 3 presents low magnification overviews of SS-PCBN-500 and SS-PCBN-800. The weld seams exhibit a satisfactory visual aspect in both samples and cross-section macrographs demonstrate no volumetric defects, confirming in theory that defect-free joints are related to the continuity of the axial force curves.

As the tool rotates faster, it can also be concluded that the additional heating generates higher temperatures and softer conditions within the metal, lowering the required axial force. As the material temperature rises with the frictional heating and plastic deformation, the atoms move further apart. The greater spacing between atoms results in a softer metal, which requires less pressure from the tool to forge together the two parent metals for a given plunge depth. However, according to Cook et al.[5], there is a drawback in increasing rotation rate. At high rotational rates, an undesirable weld flash can be created when the metal is detached and expelled from underneath the shoulder of the rotating tool; the shoulder surface shears off a thin layer of the material, which is referred to as weld flash.

3.2. Axial force profile – no defect-free joints

Figure 4 shows the axial force versus time curves during the FSW process for no defect-free joints. Figure 5 presents low magnification overviews of the welded joints.

The cross-section macrograph of SS-WRe-400 (Figure 5a) shows a lack of consolidation of the material inside the weld nugget, which is the most common defect found in FSW, known as void or wormhole. It was caused by cold processing conditions due to the combination of traverse speed, tool rotation, plunge depth and resulting insufficient axial force. Voids create porous conditions, which negatively affect the structural integrity of the weld. Facing insufficient force, the friction between the tool shoulder and the material is reduced, leading to less heat generation and lower temperatures inside the die cavity. The lack of heat does not aid the deformation of the material because the material remains in a hardened state. In addition, the colder welding condition does not promote the mixing and forging of the plasticized material. These facts caused

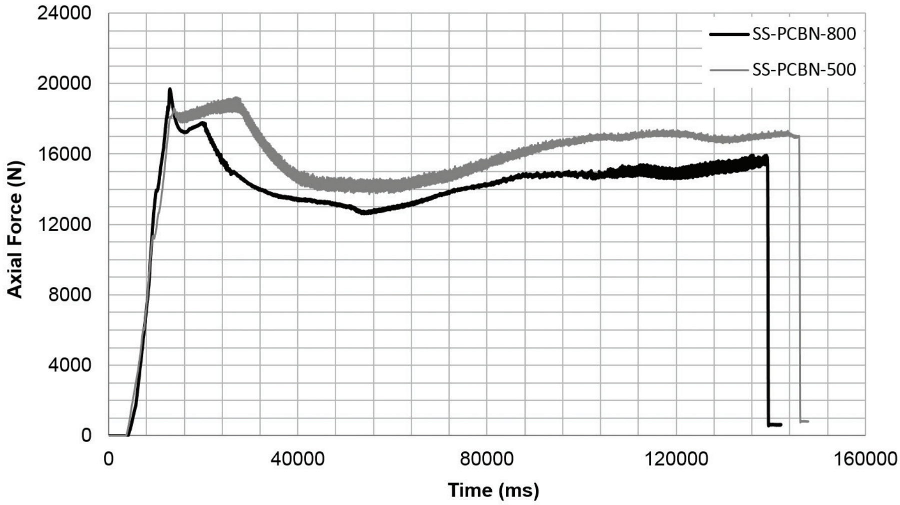

Figure 2. Profiles of axial force versus time of defect-free welded joints.

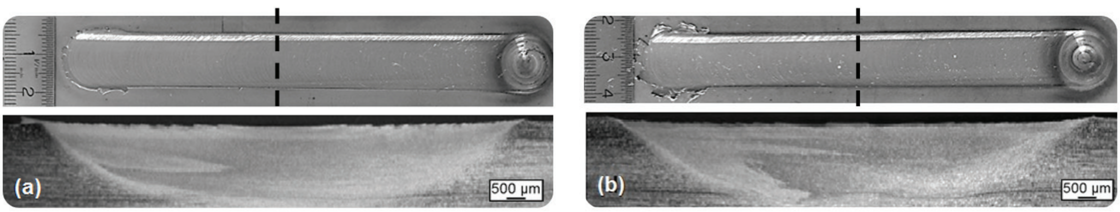

Figure 3. Macrographs of top surface and cross-section of joints: (a) SS-PCBN-500 and (b) SS-PCBN-800. The black lines on the top surfaces indicate the sections of cut.

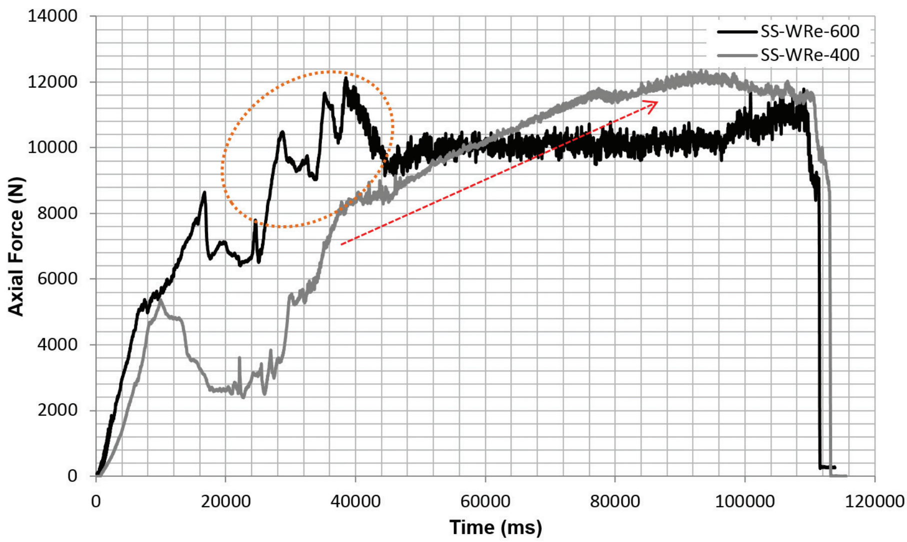

Figure 4. Profiles of axial force versus time of no defect-free welded joints.

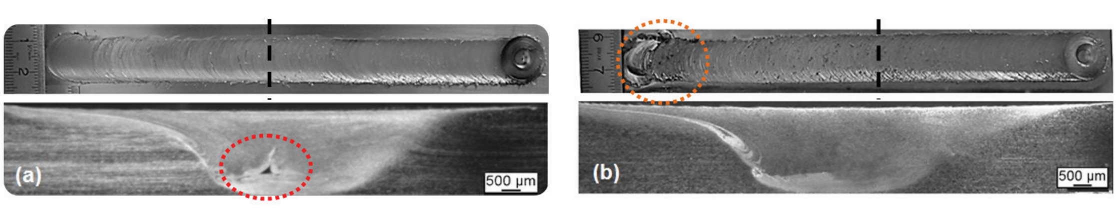

Figure 5. Macrographs of top surface and cross-section of joints: (a) SS-WRe-400 and (b) SS-WRe-600. The black lines on the top surfaces indicate the sections of cut.

an abnormal oscillation of axial force after the plunge. Consequently, axial force continues to increase, seeking to reach its stability. However, the steady-state equilibrium value was only achieved at the end of the process.

According to the model proposed by He et al.[6], porosity tends to be formed in the advancing side, very close to the pin. The wormholes and voids can be minimized by rising the axial force of the FSW tool, which is made possible by increasing the heat inside the die cavity. The heat increase will cause the metal to become softer and the voids may collapse. Considering this, another attempt was performed by increasing the rotation speed from 400 rpm to 600 rpm in order to increase the heat input of the process. However, caution should be taken when arbitrary adjusting the processing parameters to create hot processing conditions. When the process becomes excessively hot, defects such as a root-flow and nugget collapse can occur. The beginning of the top surface of SS-WRe-600 showed an evident nugget collapse. This defect was caused by a large amount of material flow from underneath the shoulder to the advancing side due to the excessive heat achieved during plunge, which resulted in a loss of cross sectional area of the weld joint, producing less load bearing capability. The collapse was directly reflected on the axial force profile, being evidenced by an abrupt oscillation on the curve. Nevertheless, as the tool started to travel far from the initial point, the heat input reduced and the equilibrium was achieved. After this point, only the natural axial force oscillation was observed. As expected, the cross-section macrograph of SS-WRe-600, extracted from a position of steady-state equilibrium, presented no apparent internal defects.

4. Conclusions

The possibility of predicting defect-free weld by analyzing and understanding AISI 304 austenitic stainless steel axial force profiles during FSW, using position-controlled mode, was investigated. The conclusion was that axial force is the first indicative of defect-free welds, which can be related to the continuity of the axial force versus time curve. Any deviation from the natural oscillation must be considered and can be associated with internal or external welding defects, such as voids and nugget collapse. Therefore, internal defects can be identified through axial force profile observations, even when weld seam exhibits a satisfactory visual aspect. The same conclusions seem to be reasonable for other types of metals.

References

1. Nandan R, Debroz T and Bhadeshia HKDH. Recent Advanced in friction stir welding – process: weldment structure and properties. *Process Mater Sci*. 2008; 53(6):980-1023.

2. Mishra RS and Ma ZY. Friction stir welding and processing. *Materials Science and Engineering*. 2005; 50(1-2):1-78. http://dx.doi.org/10.1016/j.mser.2005.07.001.

3. Meran C, Kovan V and Alptekin A. Friction stir welding of AISI 304 austenitic stainless steel. *Materialwissenschaft und Werkstofftechnik*. 2007; 38(10):829-835. http://dx.doi.org/10.1002/mawe.200700214.

4. Reynolds AP, Tang W, Gnaupel-Herold T, Prask H, Gnaupel-Herold T and Prask H. Structure, properties, and residual stress of 304L stainless steel friction stir welds. *Scripta Materialia*. 2003; 48(9):1289-1294. http://dx.doi.org/10.1016/S1359-6462(03)00024-1.

5. Cook G, Crawford R, Clark D and Strauss A. Robotic Friction Stir Welding. *The Industrial Robot*. 2004; 31(1):55-63. http://dx.doi.org/10.1108/01439910410512000.

6. He Y, Boyce D and Dawson P. Three-Dimensional Modeling of Void Growth in Friction Stir Welding of Stainless Steel. *AIP Conference Proceedings*. 2007; 980(1):25-34. http://dx.doi.org/10.1063/1.2740787.