# INFLUENCE OF ENERGY INPUT IN FRICTION STIR WELDING ON STRUCTURE EVOLUTION AND MECHANICAL BEHAVIOUR OF 304L AUSTENITIC STAINLESS STEEL[1]

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## Abstract

Stainless steels are an important class of engineering materials widely used in a variety of industries and environments. These materials, which are usually considered difficult to weld by conventional fusion welding processes, have demonstrated outstanding performance when joined by friction stir welding (FSW), a solid-state joining process. FSW input energy regulates the magnitude of the thermal cycle and the intensity of deformation taking place during the process, and it can be controlled by the welding parameters, affecting the grain features and consequently the mechanical properties of the joints. Nevertheless, there remains a lack of knowledge about the microstrutural evolution of these alloys during FSW, and its correlation with weld energy input and their respective mechanical properties, particularly for austenitic stainless steels. The objective of this article is to establish the microstructure/properties/weld energy input relationships of FS-welds with different welding parameters. Microstructural investigation of the FS-welds showed similar weld zone formation, but presented specific grain features, according to weld zone and energy input. The most significant effect was observed in the SZ. The increase of energy input led to formation of coarse recrystallized grains, a remarkable grain growth and sigma phase formation.

**Key words:** Austenitic stainless steel; Friction stir welding; Energy input; Hardness; Microstructure; Sigma phase.

## INFLUÊNCIA DA ENERGIA DO PROCESSO DE SOLDAGEM POR FRICÇÃO E MISTURA NA EVOLUÇÃO MICROESTRUTURAL E NO COMPORTAMENTO MECÂNICO DO AÇO INOXIDÁVEL 304L

## Resumo

Os aços inoxidáveis são uma importante classe de materiais de engenharia, extensamente aplicados em diversas indústrias e ambientes. Esses materiais, frequentemente considerados difíceis de serem soldados pelos métodos de soldagem por fusão convencionais, têm demonstrado um excelente desempenho quando unidos por soldagem por fricção e mistura (SFM), um processo de soldagem no estado sólido. Em SFM, a energia do processo determina a magnitude do ciclo térmico e a intensidade da deformação que ocorre no material durante o processo – energia essa controlada pelos parâmetros de soldagem – afetando características do grão e consequentemente as propriedades mecânicas das juntas. Contudo, um completo entendimento sobre a evolução microestrutural desses materiais durante o processo já mencionado e a sua relação com a energia de soldagem e propriedades mecânicas, principalmente dos aços inoxidáveis austeníticos, se faz necessário. O objetivo deste artigo é estabelecer a relação microestrutura/propriedade/energia de processo de soldas de fricção e mistura com diferentes parâmetros de soldagem. Observações microsestruturais mostraram que todas as soldas apresentaram regiões de soldagem similares, porém com características de grão distintas para cada uma das condições de soldagem. O efeito mais significativo foi observado na zona de mistura, onde o aumento na energia do processo ocasionou a formação de grãos recristalizados equiaxiais, com um considerável crescimento de grão e formação da fase sigma.

**Palavras-chave:** Aços inoxidáveis austeníticos; Soldagem por fricção e mistura; Energia de processo; Dureza; Microestrutura; Fase sigma.

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## 1 INTRODUCTION

Since its invention, the friction stir welding (FSW) process has received worldwide attention. When compared to fusion welding processes, FSW causes less distortion, changes in metallurgical and mechanical properties are minimized and the associated residual stresses are reduced. However, the ability to use friction stir welding for the joining of ferrous materials has only recently been brought to fruition because of the specialized tool material which first required development.
Stainless steels are indispensable materials in industry and their use is growing. Their areas of application will expand because there are many types and kinds of stainless steel. However, these materials have problems in stress corrosion cracking and weld decay due to sensitization in heat affected zone.(1,2) FSW has a potential to offer a weld with a minimal heat affected zone, no cracking and no macro-segregation due to solidification, and a finely recrystallized microstructure, which have been approved in relatively low melting temperature materials such as aluminum and magnesium alloys.(3)
Recently, the feasibility of FSW for stainless steels has been examined and reported, and further revitalization of research and development is advancing FSW.(4-6) The authors have been conducting FSW of austenitic stainless steels and reported the characteristics of microstructures in FS welds of 304L austenitic stainless steel. Nevertheless, there remains a lack of knowledge about the microstrutural evolution of these alloys during FSW, and its correlation with weld energy input and their respective mechanical properties, particularly for austenitic stainless steels. The objective of this article is to establish the microstucture/properties/weld energy input relationships of FS-welds with different welding parameters.

## 2 EXPERIMENTAL PROCEDURE

The base material used in the present study was a commercial hot-rolled type 304L austenitic stainless steel, 2.4 mm in thickness. The plates were friction stir welded using Gantry system composed mainly of a rigid steel bracket and a cross beam attached to the bracket that allows vertical displacement of the shaft.
A PCBN tool with a 10 mm shoulder diameter, and a 1.4 mm pin length was used in the present study. A locking collar was used to hold the PCBN and transfer torque to the tungsten carbide shank. An argon atmosphere was introduced through a gas cup around the tool to minimize surface oxidation.
All FS-welds were produced, when possible, using a unique down force in conjunction with 4 levels of energy inputs, in order to produce samples with particular parameter combination as presented in Table 1. The rotating tool pin was slowly pushed into the plate, without any preheat, until the tool shoulder came into contact with the surface of the material, which generated frictional heat to locally soften the material around the pin. The FS direction (FSD) was parallel to the rolling direction (RD) of the plate.

**Table 1.** Welding parameters

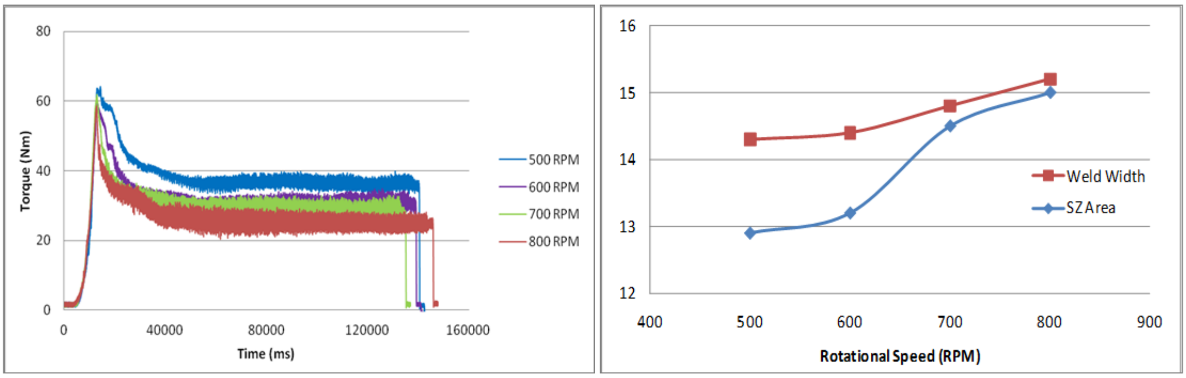
| Name | Tool Angle | Rotation (RPM) | Traverse Speed (mm/s) | Plunge (mm) |
|---|---|---|---|---|
| FSW-PA-CS-1 | 0 | 500 | 2 | 1.4 |
| FSW-PA-CS-2 | 0 | 600 | 2 | 1.4 |
| FSW-PA-CS-3 | 0 | 700 | 2 | 1.4 |
| FSW-PA-CS-4 | 0 | 800 | 2 | 1.4 |

The energy input of FSW should be direct proportional to rotation speed. Hence, as rotation speed increases the welding energy input also increases. Mechanical output analysis was made to confirm the correlation mentioned.

Microstructural observations were performed by optical microscopy (OM). The specimens were cut perpendicular to the welding direction and mechanically ground with water abrasive paper and polished with OPS suspension, and etched electrolytically in a solution of 10% oxalic acid-+90% water with a power supply set to 19 V for about 18 s. Mechanical assessment was carried out using microhardness, across the welding transverse section previously polished and transverse to the weld seam, using a conventional Vickers indenter with HV 0.5 load for an indent period of 10 seconds. The measurements were conducted at the mid-thickness of each workpiece, along the base material and FSW zones, maintaining 0.3 mm spaces between each indentation.

## 3 RESULTS AND DISCUSSION

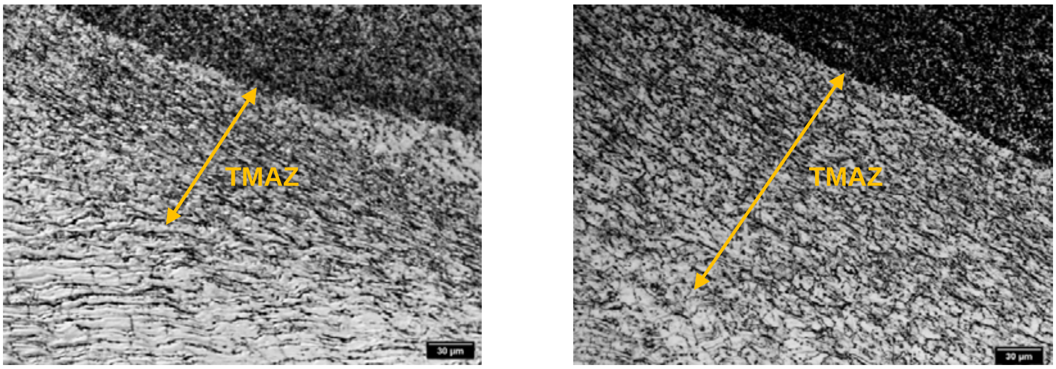
Through torque profile analyses during the process was observed that the energy input of FSW has direct proportions with rotation speed ($\omega$) (Figure 1a). Torque was significantly affected for rotational speed variation. This behavior suggest that the increase of rotation speed generates high plastic deformation of the workpiece, as a consequence, torque decreased once that the material in front of the tool was softer when higher rotation speed is applied, as expected. Also, when tool displacement started torque remained constant throughout the process for both cases, resulting on welds with no groves or other superficial defects. Figure 1b shows the relationship between rotational speed and stir zone areas, at a constant traverse speed value. Weld width and SZ area increased quantitatively for high rates of ω, confirming higher levels of plastic deformation.



(a) (b)

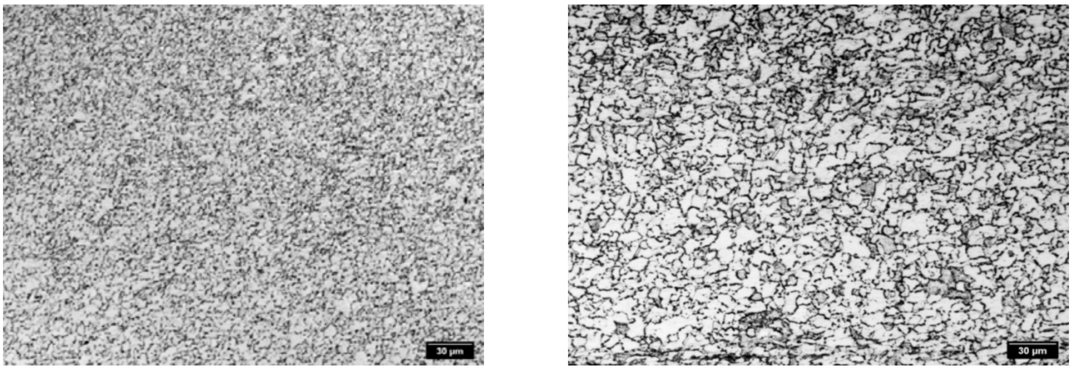
**Figure 1.** (a) Torque profiles during the process for different rotational speeds; (b) the effects of rotational speed on weld width and SZ area.

Unlike aluminum and most non-ferrous materials, which show little or no visible change during FSW due to increases in temperature, a color change occurred when stainless steel was welded. The tool shoulder reached a bright orange color within a few seconds of making contact with the plate. This indicated temperatures of over 1,000ºC. The tool shoulder maintained its bright orange color throughout the weld.
All welds had no internal discontinuities. Optical micrographs revealed four FSW typical regions: base material (BM), heat affected zone (HAZ), thermomechanically affected zone (TMAZ) and stir zone (SZ). Comparing the microstructures of 500 RPM and 800 RPM welds, it was observed that by increasing ω or energy input, HAZ and TMAZ regions also became slightly larger (Figure 2). The metal in the TMAZ is located at the edge of the tool. The plastic flow and deformation of grains occurred because of the rotation and stir of the tool and presented a recovered microstructure. However the most significant effect is observed in the SZ. An increase in ω increases the recrystallized grain size. Friction stir welding at higher ω leads to an increase in both degree of deformation and peak temperature of thermal cycle. The increase in the degree of deformation gives more energy to both processes, recrystallization and grain grow. Also the increase in peak temperature of thermal cycle leads to generation of coarse recrystallized grains, and also results in remarkable grain growth. The average grain size measured by the mean linear intercept method for all high angle boundaries was approximately 4 µm and 8 µm for the 500 RPM and 800 RPM welds, respectively (Figure 3).



(a) (b)

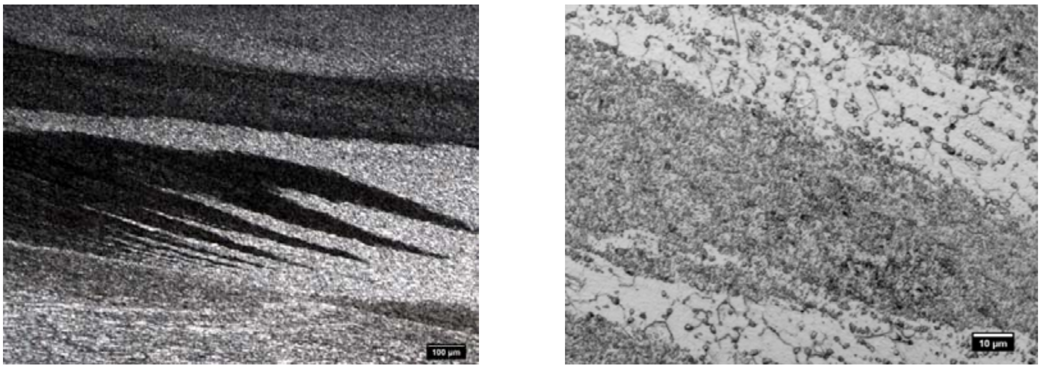
**Figure 2.** Comparison of TMAZ size of two 304 AAS FS welded samples welded with different ω; (a) 500 RPM; (b) 800 RPM.



(a) (b)

**Figure 3.** Effect of input energy on hardness profile and SZ grain size; (a) 500 RPM; (b) 800 RPM.

The advancing side of the SZ of the 800 RPM weld showed a different region, with a very refined microstructure (Figures 4a and 4b). The same microstructure was presented by Park, Sato  e Kokawa.(7) In his work, through EDS Analysis and TEM images, sigma phase including the numerous stacking faults was observed to be formed. It was suggested that the rapid formation of the sigma phase is related to the transformation of austenite to delta-ferrite in the stir zone, from introduction of high strain and dynamic recrystallization during FSW, being possible to observe that as the rotation speed increased sigma phase was formed. Because of its brittleness, sigma phase deteriorates materials proprieties such as corrosion and tensile resistance.



(a) (b)

**Figure 4.** Optical micrographs in the stir zone (SZ) of the 800 RPM weld; (a) and (b) refined structure found in the advancing side of the SZ.

In each of the FS-welds, the hardness distribution increased from the unaffected BM region toward the SZ. The SZ and TMAZ showed to have smaller grain size than the BM. It is suggested that the high dislocation density and sub.-boundaries formed during dynamic recrystallization and recovery processes result in higher hardness in the SZ and the TMAZ than that in the BM, as discussed previously. It was also possible to observe the effect of energy input on hardness profiles, especially in the SZ, as discussed previously.

**Figure 5.** Comparison of hardness profile FS welded samples welded with different energy inputs.

## 4 CONCLUSION

The metallurgical and mechanical properties welded zones of friction stir welded 304L austenitic stainless steel, FS-welded using different energy inputs, were investigated. HAZ and TMAZ sizes regions became slightly larger by increasing energy input. The SZ and TMAZ in the all welds were characterized by dynamically recrystallized and recovered microstructures, respectively. Since grain size depends primarily on the weld energy input, higher energies promoted larger grain sizesdirectly impacting on the hardness The hardness of the weld was higher than that of BM. Sigma phase was detected in the advancing side of the joint welded with the highest rotation speed, 800 RPM, which should be related to the transformation of austenite to delta-ferrite, from introduction of high strain and dynamic recrystallization during FSW.

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