The Influence of Fast Diffusers in Friction Stir Welding of Titanium Alloys

J. Wolk[‡], R. K. Everett*, S. Szpara[‡], C. Scheck[‡†], M. Zupan[†]

[‡] Naval Surface Warfare Center - Carderock Division
Bethesda, MD 20817

***Naval Research Laboratory**
Washington, DC 20375

[†]University of Maryland Baltimore County
Baltimore, MD 21250

Keywords: x-ray, tomography, friction stir welding, titanium

Abstract – Friction stir welding (FSW) of alpha and near alpha alloys has been shown to be challenging with respect to creating sound, repeatable welds. FS welds of alpha and near alpha alloys often show the presence of voids with variable weld consistency, thus limiting the use of friction stir welding of these alloys. In this paper, we discuss the use of nickel (Ni) foil incorporation into the weld joint for significant forging load reduction, enhanced surface finish, reduction of void formation, and increased travel speeds. Nickel (Ni) foil markers of varying thicknesses were incorporated in 6 mm (0.25 inch) thick CP titanium and Ti 6-4 friction stir welds of various joint geometries using simple frustum-shaped tungsten based tools. The Ni foil shows localized effects that result in enhanced weld consolidation. The influence of Ni as a fast diffuser in the titanium system and tungsten system was examined through the use of X-ray computed microtomography (XCMT), as well as microstructural analysis using optical microscopy, scanning electron microscopy, and electron backscatter diffraction. Microtensile testing of materials from the weld and transitions zones measures mechanical properties comparable to the base metal and will also be discussed.

I. Introduction – Titanium (Ti) and titanium alloys show excellent mechanical, physical, and corrosion properties for marine applications. Additionally, weight reduction benefits make titanium alloys potential candidates for future weight critical platforms. The Navy after next is exploring smaller, faster, lightweight ships for more rapid response as structural weight issues will become increasingly important for future combatants.

Titanium alloys provide weight reduction and reduced total operational costs because of high corrosion/erosion resistance. However, high fabrication costs required to minimize weld contamination may limit titanium applications. Titanium alloys are traditionally joined through conventional fusion welding techniques such as gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). However, to prevent atmospheric weld contamination (oxygen and nitrogen) and moisture contamination (hydrogen), inert shielding gas around the weld torch and shielding gas trailing the weld torch is necessary. Shielding and strict inspection requirements are significant cost drivers in titanium welding.

Friction stir welding (FSW) is a potential welding technique for titanium that has shown promise for joining aluminum and steel. Friction stir welding uses a non-consumable tool to generate frictional heat to plastically deform and mix metal to form a consolidated joint [1]. Because FSW does not reach melting temperatures, it also provides reduced distortion from residual stresses and heat due to melting during traditional gas metal arc welding (GMAW). FSW has been widely developed and is accepted in the automotive and aerospace industry soundness. Traditionally, the cost for re-work and repair of a Ti arc weld can be more than 20 times the cost of the original weld. The high cost is due to a limited number of inspection techniques, rigid inspection requirements, and the difficulty of welding titanium. FSW of Ti alloys can provide a cost savings by reducing the time required to reach the necessary dew point for the targeted application. For complex structures, this time reduction can save man hours per day by reducing the time to reach the required dew point. Additionally, joining below melting temperature may reduce contamination. A highly automated process, FSW also has the potential to reduce inspection requirements. Early investigations show promise for friction stir welding of titanium alloys [2-4], such as Timetal-21S (a metastable β-phase alloy), Ti-6-4 (a α/β alloy) and Ti-CP (a single phase α alloy) but there has been limited work in titanium alloys. Commercially pure Ti has been found to be challenging to friction stir weld with high weld quality and consistency.

This paper discusses incorporating Ni foil into the weld joint of titanium plates to significantly reduce forging loads, enhance surface finish, reduce of void formation, and increase travel speeds.

II. Procedures

Ti-CP and Ti-64 plates, 305 x 152 x 6 mm thick, were prepared for FS welding by mild abrasion and degreasing. A 0.004 mm thick commercially pure, annealed Ni foil strip was placed in the joint interface and held in place by clamping. The orientation of the foil with respect to the weld joint will be discussed in the results section.

FS welding was performed on MTS ISTIR PDS systems at both NSWCCD and the South Dakota School of Mines using a 1% lanthanated tungsten tool (WL10) with a tapered probe and narrow shoulder. The tool shoulder diameter was 22.86 mm (0.9 inch). The inserted region is 7.92 mm (0.312 inch) in diameter tapering at 20 degrees to a depth of 6.35 mm (0.25 inch) where the final diameter was 4.75 mm (0.187 inch). This two-piece tool utilized a Densimet tool holder.

After welding, samples were sectioned from regions containing foil and no foil for microstructural characterization and tomographic analysis. The details of metallographic and tomographic preparation can be found in Everett et al. [5].

III. FSW

Friction stir welds in 6mm (0.25 in) Ti-CP and Ti-64 were fabricated with 0.1 mm (0.004 inch) Ni foil placed in the butt joint in the direction of travel. Initial welding parameters were 300 rpm and a travel speed of 25.4 mm/min (1.0 in/min) based on prior work examining a welding envelope of Ti alloys. The foil was located halfway down the weld at approximately 152.4 mm (6 inches) from the starting edge of the plate. The tool was plunged into base material to form a standard FS weld joint before encountering the Ni foil. During welding of Ti-CP with no foil present, plunge z-loads reached over 3000 lbs and loads were un-steady until the weld reached the foil. Upon interaction with the foil, axial and forging loads were dramatically reduced and stabilized to an averaging of 500 lbs x-force and 1100 lbs z-force (Figure 1). The stabilization effect was also observed within the machine system with a similar reduction of machine chatter after welding through the foil. The surface finish was observed to change with and without foil, as shown in Figure 2. In contrast, the introduction of foil within the Ti 6-4 alloy resulted in a significant increase in axial and forging loads. Axial and forging loads without foil in the Ti 6-4 FS weld were steady and averaged 500 lbs x-force and 1000 lbs z-force. Introduction of the foil caused increased loads peaking at over 4000 lbs z-load and over 2000 lbs x-load (Figure 3). Further microstructural analysis showed the addition of foil caused defect consolidation in Ti-CP with the addition of foil and formation of voids in Ti-64l.

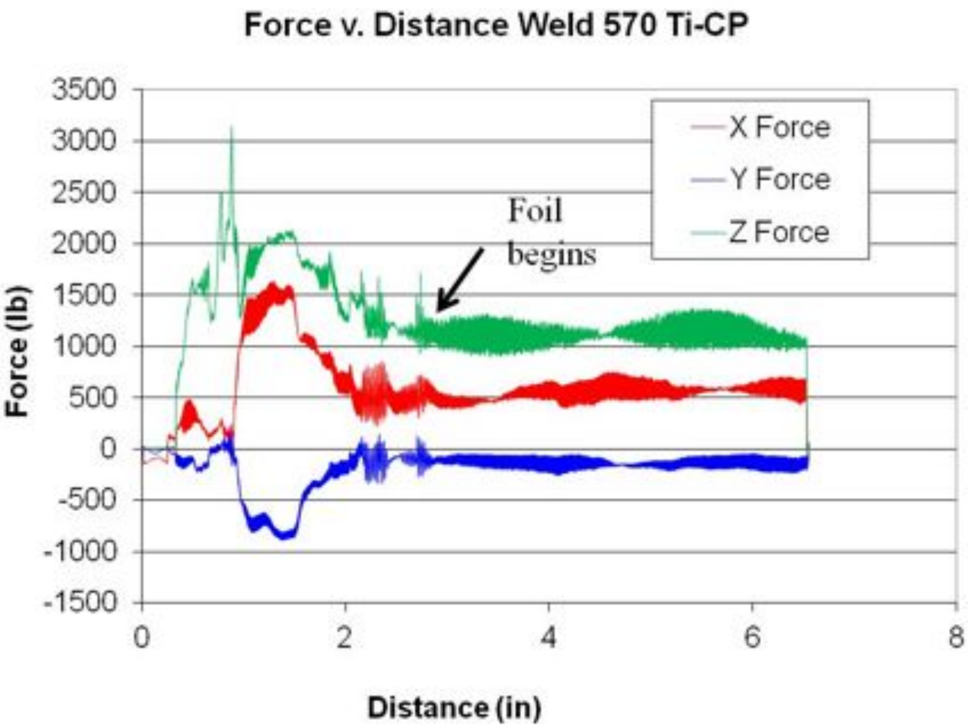


Figure 1. Load versus distance with FS welding of Ti-CP with and without foil. The addition of foil resulted in a significant load reduction and machine chatter.

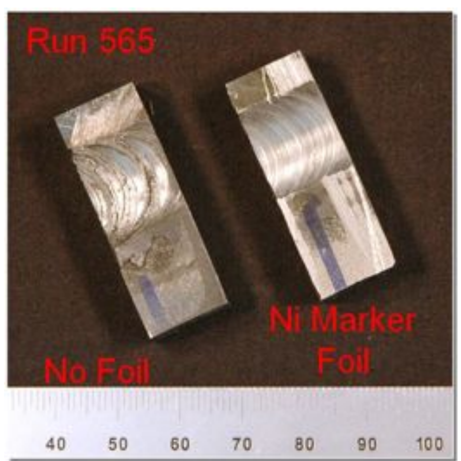


Figure 2. Macro surface images of FSW of Ti-CP with and without Ni foil. The addition of foil resulted in a smoother weld surface.

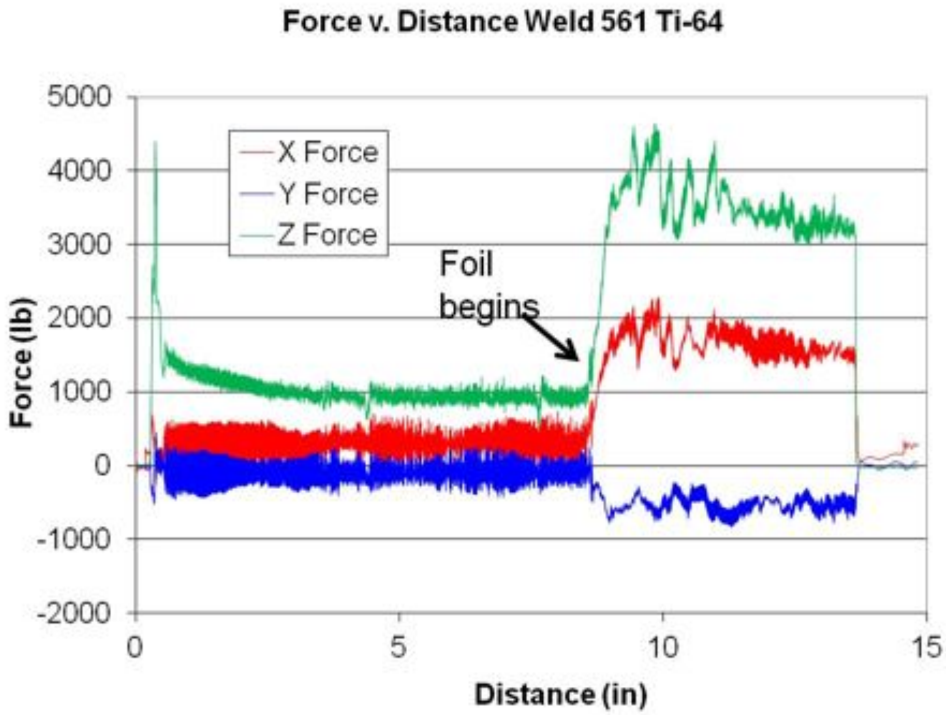


Figure 3. Load versus distance with FS welding of Ti 6-4 ELI with and without foil. The addition of foil resulted in a significant higher load and machine chatter.

This dramatic effect was repeated on a similar MTS system at the South Dakota School of Mines with the same welding parameters. Ti-CP welds fabricated with the Ni foil in the direction of travel showed stable welding loads with a downward forging force of approximately 1000 lbs. Welding Ti-CP with thinner Ni foil 0.05 mm (0.002 inch) foil in the same configuration produced similar welding loads. Both sets of welds were sound and defect free.

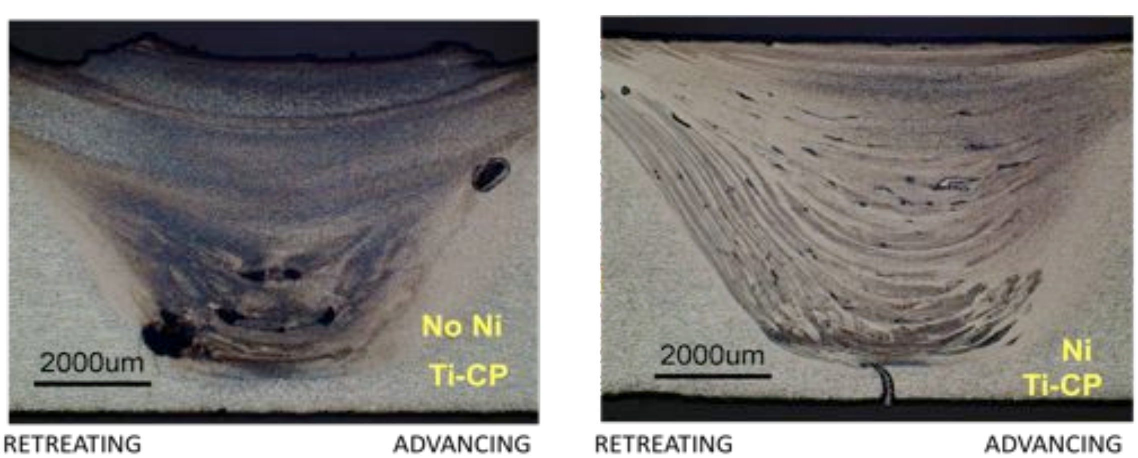
Additional trials focusing on Ti-CP examined the effect of tool rotational speed and travel speed on the weld consolidation using 0.1 mm (0.004 inch) Ni foil throughout the weld. At the start of the weld, tool rotational speed was 200 rpm and rotational speed increased an additional 100 rpm every 63.5 mm (2.5 inches) until rotational speed reached 500 rpm. During this trial, tool travel speed remained constant at 25.4 mm/min (1.0 in/min). At the slowest rotational speed of 200 rpm, forging loads were highest reaching approximately 2500 lbs. . Forging loads were lowest at the highest rotational speed, 500 rpm, resulting in average loads well below 1000 lbs. A second set of experiments maintained rotational speed at 300 rpm and varied travel speed from 12.54 mm/min (0.5 inch/min) at the start of the weld and steadily increased travel speed by 12.54 mm/min every 63.5 mm (2.5 inches) until travel speed reached 50.8 mm/min (2.0 in/min). Varying the travel speed resulted in higher loads approaching 2000 lbs when traveling at 50.8 mm/min. However, the surface finish of this weld was significantly rougher and contained a wormhole defect formed during the higher travel speed. Examination of the associated torque measurements showed lower, more stable spindle torques at increasing rpm and constant travel speed while spindle torques showed slight increases at increasing travel speeds and a constant rpm. This indicates that rotational speed plays a larger role than travel speed in weld consolidation. A sound weld was fabricated at 500 rpm and 101.6 mm/min (4.0 in/min) using the addition of Ni foil.

IV. Analysis

Metallographic samples taken from regions with and without Ni foil from a Ti-CP weld and Ti-64 weld are irregular in nature and are similar to defects found in near α titanium FS welds. Welding with the Ni foil resulted in consolidation of the subsurface voids. Based on the optical macrographs, Ni is distributed evenly throughout the weld with a concentration of fine particles at the bottom of the weld. Examination of the optical macrographs of the Ti-CP FS weld before etching reveal no intermetallic formation between the Ni flakes and the Ti-CP (Figure 5). The Ni foil at the joint line shows the initial foil deformation and incorporation into the weld. Scanning electron microscopy (SEM) examination of these specimens shows Ni foil particle deformation in the Ti CP matrix. Energy dispersive x-ray spectroscopy (EDS) also shows some diffusion of Ni into the surround matrix. In contrast to the Ti-CP, the optical macrographs of Ti 6-4 show subsurface void formation on the retreating side after introduction of Ni. In the Ti 6-4, the stir zone is narrower when welded with Ni and there is limited Ni dispersion throughout the Ti 6-4 weld. An onion-ring like phenomenon and distinct flow arm appears in the Ti 6-4 with Ni foil, similar to structures found in friction stir welding of aluminum alloys.

Vickers microhardness traverses across the centerline of the weld from retreating to advancing side and from the top of the weld to the bottom of the weld show no distinct hardness differences in Ti-CP FS welds with and without the Ni foil (Figure 6). Mechanical properties determined through the use of microtensile tests performed by University of Maryland Baltimore County show yield strengths for the stir zone between 459-463 MPa and ultimate tensile strengths between 613-620 MPa. Typical properties of CP Ti Grade 2 range from yield strengths of 335-545 MPa and ultimate tensile strengths of 510-605 MPa [6]. The microtensile tests of Ti-CP welded with Ni foil show slightly higher yield and ultimate strengths.

In addition to metallographic analysis and mechanical properties, x-ray computed microtomography was performed on the Ni foil FS welds. The Ni foil deposited throughout the weld served as a marker that provided information on the material flow in Ti-CP FS welds. The Ni marker showed distinct differences in material deposition with marker materials being deposited on the retreating side. The markers also showed 4 distinct regions, distinguished by marker Ni foil angles, within the weld. We believe foil alignment within these regions indicates the depth of heat penetration within the plate during welding. Details on the tomographic characterization can be found in Everett et al. [5].



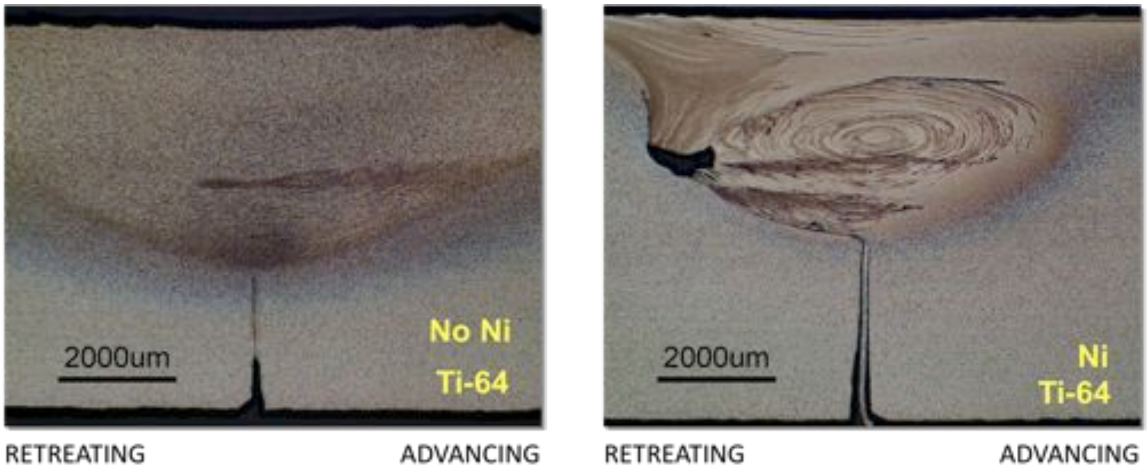


Figure 4. Optical metallography of weld cross-sections fabricated with and without Ni foil in Ti-CP and Ti-64.

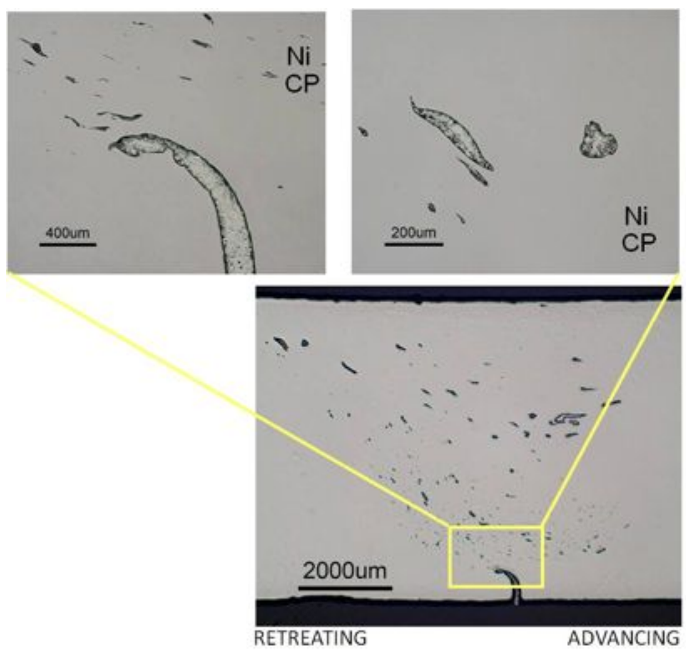


Figure 5. Optical macrographs of welds with Ni foil before etching reveal no intermetallic formation between the Ni flakes and the Ti-CP.

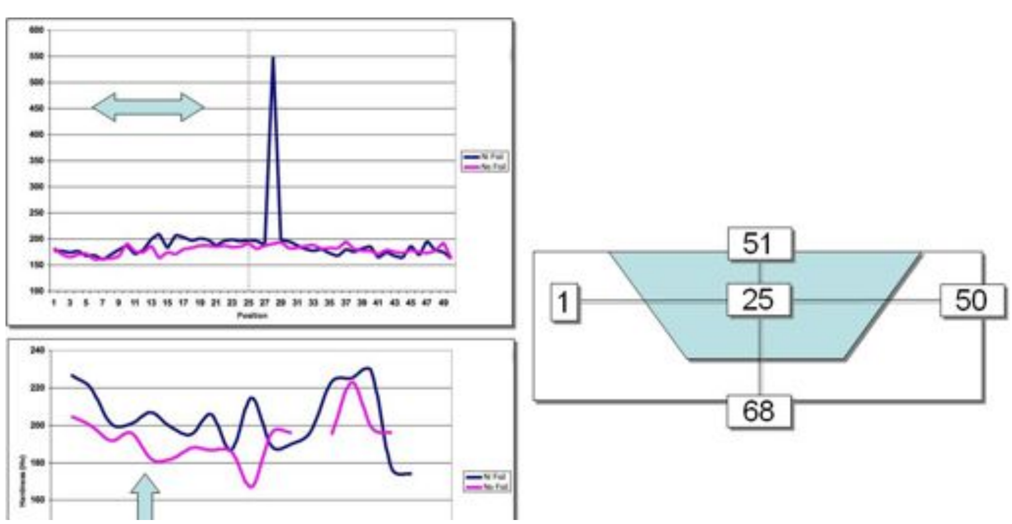


Figure 6. Hardness traverses across the centerline of the weld from retreating to advancing side and from the top to the bottom of the weld.

V. Discussion

Nickel foil markers of varying thicknesses were incorporated in 6 mm (0.25 inch) thick Ti-CP and Ti 6-4 friction stir welds of various joint geometries. The Ni foil was used to successfully analyze material flow in Ti FS welds through the use of x-ray computed microtomography and metallographic characterization. The Ni foil additions also significantly altered friction stir welding conditions within the base material for both the Ti-CP and Ti-64. Most notably, the addition of Ni foil when friction stir welding Ti-CP resulted in forging load stabilization, load reduction, improved surface finish, and weld consolidation in comparison to welding without the Ni foil.

To further understand the effects of Ni within the Ti-CP friction stir welding system, a review of available literature suggests a number of effects may be occurring. Nickel, a known β stabilizer, also shows the ability to be a fast diffuser within the α Ti system [7]. The rapid interstitial solubility in the hcp α system combined with the bcc β phase stabilization may result in local phase stabilization. This theory is further enhanced by Bhaskaran et al. [8] who discusses two potential modes of eutectoid decomposition as well as a competing martensitic reaction within the Ti-Ni system. In a pure Ti system, compositions up to 4.5-6.9% Ni leads to α+β formation between 765-770°C [9]. This temperature range for α+β formation is within the range of experimentally measured temperatures of friction stir welded Ti-CP [10].

Future work is planned to examine the effect of other known fast diffusers such as Fe and Co (and potentially their alloys) within the Ti system to locally affect the material. Additionally, further experiments are planned to examine the placement of the marker foil and characterize the effects of the foil placement on friction stir welding. Mechanical properties and in depth microstructural characterization are planned to further advance the understanding of material flow within the friction stir process.

VI. Summary

Nickel foil markers were incorporated in 6 mm (0.25 inch) thick CP titanium and Ti 6-4 friction stir welds. The Ni foil within the Ti-CP system shows localized effects that result in enhanced weld consolidation and significant load reduction. The addition of Ni within the Ti-CP system allowed for successful defect free welding of 6mm thick material up to travel speeds of 101.6 mm/min (4.0 in/min). The influence of Ni as a fast diffuser in the titanium system was examined through the use of microstructural analysis and X-ray computed microtomography (XCMT). Microtensile testing of materials from the weld shows mechanical properties comparable to the base metal.

Acknowledgements – The authors gratefully acknowledge funding from the Office of Naval Research, and the Basic Research Program of the Naval Research Laboratory. We furthermore acknowledge the assistance of Drs. Jerry Feng and Christian Widener.

References

[1] W.M. Thomas, et al. Friction Stir Butt Welding, International Patent Application PCT/GB92/02203 and G.B. Patent Application 9125978.8 1991

[2] R.S. Mishra and M.W. Mahoney. Friction Stir Welding and Processing. ASM (2007)

[3] W.B. Lee, C.Y. Lee, W.S. Chang, Y.M. Yeon, S.B. Jung. "Microstructural investigation of friction stir welded pure titanium." Materials Letters 59 (2005) 3315-3318

[5] R. K. Everett, A. C. Lewis, J. Wolk, C. Scheck, S. Szpara, S. Nimer, M. Zupan. "X-Ray Tomography of CP Titanium Friction Stir Welds Incorporating Fiducial Markers." 9th International Friction Stir Welding Symposium (2012).
[6] http://cartech.ides.com/
[7] Y. Mishin and Chr. Herzig, "Overview No. 136: Diffusion in the Ti-Al System," Acta Materialia, 48(2000) 589-623.
[8] T. A. Bhaskaran et al., "On the Decomposition of B Phase in Some Rapidly Quenched Titanium-Eutectiod Alloys," Met. Trans A, Vol 26A (June 1995), pp 1367-1377.
[9] S. Krishnamurthy, et al. "Beta-Eutectoid Decomposition in Rapidly Solidified Titanium-Nickel Alloys," Met. Trans A Vol 19A (Jan 1988)
[10] J. Wolk et al. "Friction stir weldability of Ti alloys." NSWC ILIR Presentation. (2010)