Collision Welding of Tungsten Alloy 17D and Copper Using Vaporizing Foil Actuator Welding

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Abstract

The objective of this study was to implement collision welding of tungsten alloy 17D (6.5% Ni, 3.3% Fe) and copper at a laboratory scale and subsequently investigate the relationship between interfacial structure and mechanical properties. Vaporizing Foil Actuator (VFA) has recently been demonstrated as a versatile tool for metalworking applications, such as impact welding of dissimilar materials. Its implementation for welding is termed as VFA welding or VFAW. With 8 kJ input energy into an aluminum foil actuator, a 0.5 mm thick Cu110 alloy sheet was launched toward a tungsten alloy target resulting in a collision at a velocity of 580 m/s. The two sheets were found to be welded in the region where the collision velocity and angle were optimal. This range, termed as the welding window was found to be narrow for this combination of target and flyer materials. Scanning electron microscopy of sectioned samples showed regions of wavy interface with significant plastic deformation on both sides. Microhardness tests revealed significant increase in hardness near the interface. Instrumented peel tests showed that the welds were quite strong with peel strength of 60 N/mm.

Keywords

Collision welding; VFAW; copper; tungsten alloy; photonic Doppler Velocimeter (PDV); wavy interface

1 Introduction

Tungsten has one of the highest melting points and strengths among metals. Due to this, it is a suitable material for applications which require high wear resistance and heat resistance. However, in many of these applications, the tungsten tool has to be joined to a different material which can provide mechanical toughness or can conduct away the heat. Copper, because of it high thermal conductivity is an ideal material to be used as a heat sink. Tungsten, due to its high melting point, is very difficult to weld to another material using traditional welding techniques. Therefore, there is a need for exploring other methods. Mitteau et al [1] used electron beam welding for successfully joining tungsten and copper. Manikandan et al. [2] demonstrated underwater explosive welding of tungsten foil and copper, but there are inherent issues with use of explosives. In this work, collision welding of a copper flyer sheet to a tungsten alloy 17D target plate has been attempted using vaporizing foil actuator welding (VFAW). To induce some ductility, some elements such as nickel, iron, and copper are often mechanically alloyed in small quantities with tungsten and the resulted composite is termed as a tungsten alloy.

VFAW is a novel technique for collision welding at a laboratory scale and was developed by Vivek et al [3]. Vaporizing Foil Actuators (VFA) are based on the phenomenon of rapid vaporization of thin metallic foils and wires caused by passage of a capacitor bank-driven current, on the order of 100 kAmps [4]. The burst of the conductor is accompanied with a high-pressure pulse which, as in the case of VFA, can be used for working metal at high strain rates. VFA has been applied toward a variety of impulse-based metal working operations such as impact welding, embossing, shearing, dynamic powder consolidation, shape calibration, and closed-die forming [5]. This paper focuses on impact welding application of VFA. Copper-titanium, aluminum-copper, aluminum-magnesium, titanium-steel, copper-steel welds were created by Vivek et al. under the same set of input electrical parameters. Flyer sheet impact velocities up to 670 m/s were measured. The weld interfaces were found to have significantly different structures and strengths. Some of the welds, such as copper-titanium, had high peel strength of 30 N/mm and had typical wavy interface, free of intermetallics and voids. However, a few others like steel-titanium were found to be weak and riddled with interfacial defects. It was noted that the welding parameters were not optimized for each combination. It was also shown that some of the welds which were weak in peel, failed in a parent material when subjected to lap shear test commonly applied for lap welds created by MPW. Therefore, peel test was proven to be more discriminatory in terms of quality of a weld, and will be used in this study as well.

Impact welding has been traditionally practiced using explosive driven pulses or less commonly by electromagnetic launch of flyers. Critical diameter [6], increasingly stringent regulations, and inability to scale down the process are some issues due to which explosive welding (EXW) finds limited application in traditional industrial environments. The most significant drawback of magnetic pulse welding (MPW) is the limited magnetic pressure that the actuators can operate at without catastrophic failure [7]. Additionally, magnetic pulse technology works efficiently only for combinations where the flyer sheet is electrically conductive or is driven by an electrically conductive material such as copper [8]. VFAW can be used to create welds of the length scales similar to that of MPW, and can make flyers reach velocities similar to those during EXW. The issue of actuator longevity does not exist as the foil actuator, which is disposable, can be easily replaced after every experiment at a low cost.

A set up very similar to the one used by Vivek et al [3] was used here to weld a 6.25 mm thick tungsten alloy 17D plate with 0.5mm thick copper sheet. The welded samples were subjected to peel tests, optical microscopy, and microhardness tests.

2 Experimental Procedure

The energy source used in these experiments was a Maxwell Magneform capacitor bank with a total capacitance of 426μF, inductance of 100 nH, and short circuit current rise time of 12 μs. When charged to the maximum voltage of 8.6 kV, this capacitor bank can supply 16 kJ of electrical energy.

Tungsten alloy 17D (ASTM B 777 Class 1 Type 2) was used as the target material. As supplied, this alloy contained 6.75% nickel and 3.3% iron. The tensile strength was rated at 860 MPa and the strain to failure was 6.5%. This material will be referred to as W-alloy in this paper. The average hardness was measured to be 378 HV. Rectangular strips, 25 mm x

55 mm, were cut out from 3 mm thick W-alloy plates. Commercially pure copper (99.99% pure) was used as the flyer material. Square strips, 75 mm x 75 mm, were cut out of 0.5 mm thick copper sheet. The initial average hardness of the copper used in this study was measured to be 95 HV.

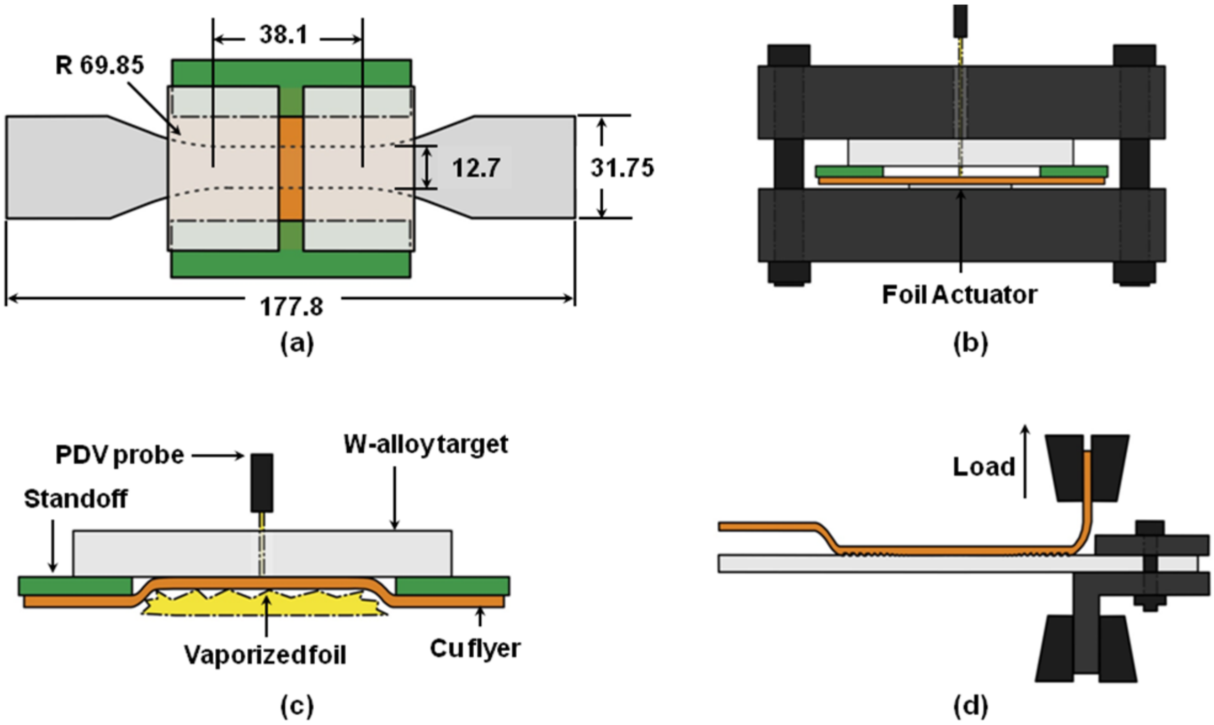

Figure 1: Vaporizing foil actuator welding (VFAW) set up for welding Cu110 with W-alloy. (a) top view of the foil actuator, flyer sheet, standoff, and target stack, (b) side view of the stack along with the positioning of the photonic Doppler velocimeter (PDV) probe, (c) formation of weld after foil actuator's vaporization, (d) peel testing set up.

A schematic of the VFAW set up is shown in Figure 1. Aluminum foil actuators of thickness 0.0762 mm and shape as shown in Figure 1a were placed underneath the flyer sheets which were stood off from the W-alloy target plates at a standoff distance of 1.6 mm. The horizontal gap between the standoffs was 30mm. The standoffs were inserted to provide sufficient distance for acceleration of the flyer plates. The capacitor bank was charged to an energy level of 8 kJ and discharged through the foil actuator. Passage of the capacitor bank-driven current, on the order of 100 kAmps, through the foil actuator caused its rapid vaporization, thereby leading to a high pressure pulse which was used for launching the flyer sheet at high speed toward the target. The thick steel backing block ensured that the expanding plasma, formed from foil actuator's burst, did most of the mechanical work on the flyer sheet. A hole drilled through the backing blocks and the gap between W-alloy target plates provided a line of sight for a focuser probe of the Photonic Doppler Velocimeter (PDV) [9].

Use of PDV as a diagnostic tool for impulse metal working applications has been discussed by Johnson et al. [10]. PDV utilizes the interference of original and reflected, Doppler-shifted laser to measure the velocity of the object from which the laser is reflected. Most of the transmission of light happens inside fiber-optics, with the laser going out into or collected back from free air via focusers, collimators or, in some cases, bare fibers. The PDV used here can measure velocities up to 1550 m/s with a temporal resolution of 1 ns for a time duration of 2 ms. Discharge current was measured by a 100kA:1V Rogowski coil, and a 1000:1 voltage divider was used to measure voltage.

The welded sample was sectioned using a circular abrasive saw and either mounted for microscopy and hardness testing, or subjected to peel testing. Microhardness testing was done along two lines across the wavy interface. One line went across the crest of the wave and the other line traversed across the trough. A diamond indenter with 200 gm load was used for the W-alloy side while a 50 gram load was used for the copper side. For peel testing of the welded samples, the flyer sheets were bent to 90° with respect to the target plate and the samples was pulled apart using a MTS 831.10 load frame moving at a speed of 0.1mm/sec. The peel strength of the weld was normalized by dividing the sustained load by the width of the sample being peeled in line with the work of Kendall et al [11].

3. Results and Discussion

The temporal evolution of the flyer sheet's velocity is shown in Figure 2a. This figure also illustrates the variation of current and voltage with time, indicating that a maximum current of 127 kA was reached within 10µs of discharge and the foil burst occurred shortly after. Plotted in Figure 2b, the displacement was calculated by integrating the velocity data with respect to time and it was found that the flyer collided with the target at 550 m/s after travelling 1.6 mm.

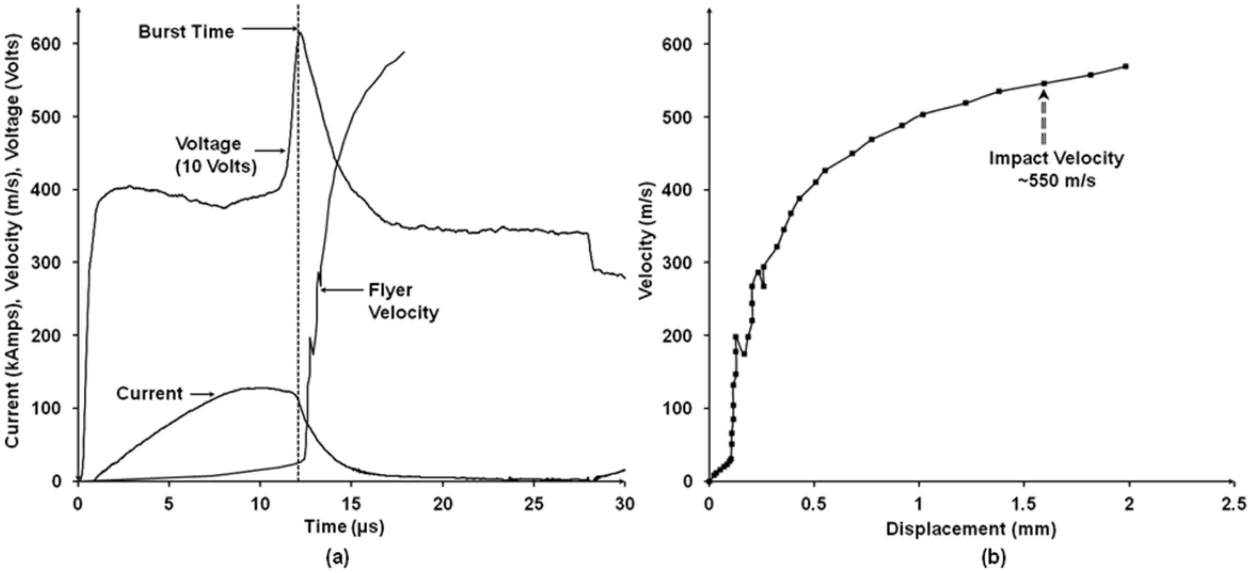

Figure 2: Results of the diagnostics run during the VFAW experiment. (a) Temporal evolution of current, voltage and velocity with 8 kJ input energy into a 0.0762 mm thick aluminum foil, (b) Velocity of the flyer plate plotted against distance travelled indicating impact with target plate at 550 m/s

The welded sample and micrograph of a wavy region of the welded interface is shown in Figure 3. Since the W-alloy was mechanically alloyed, distinct regions with higher iron and nickel content were distributed in the tungsten matrix. Elongation of these regions along the weld interface, as seen in the micrograph with highest magnification indicated severe plastic deformation. Similar effect would be seen on the copper side if it was etched. The weld was created outside the region of zero angle impact directly above the former area of the foil actuator. The cross section across the weld shows two distinct regions where welding occurred. The width of the wavy region or the "good weld region" was nearly 0.5 mm which shows that the range of collision velocities and angles for which good welds are created for this pair of materials is rather limited.

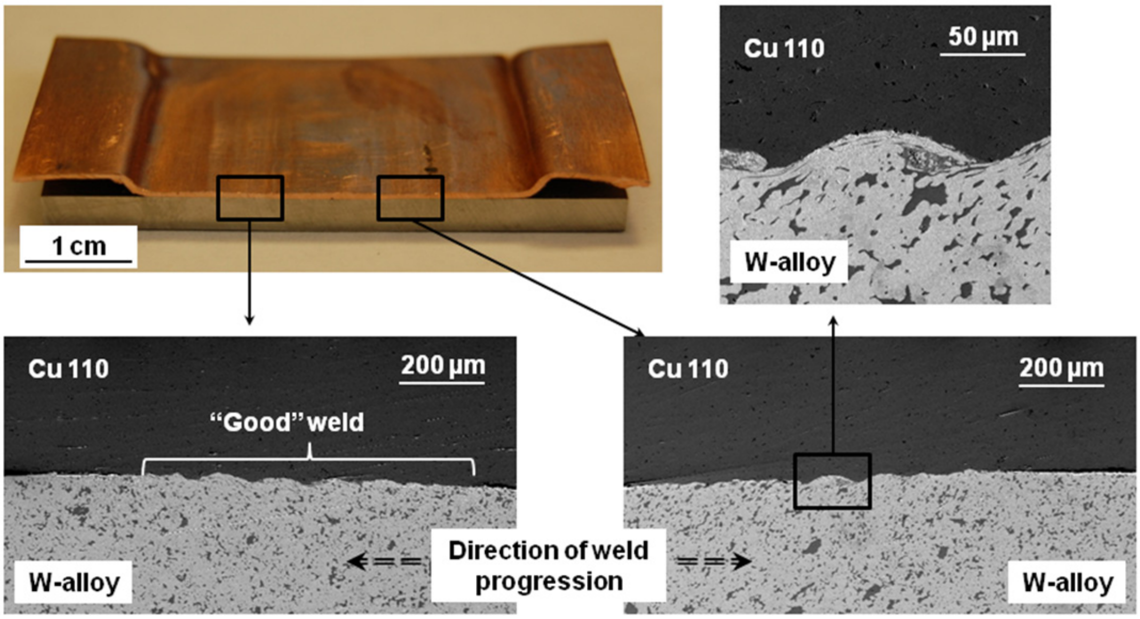

Figure 3: Images showing the welded Cu-W alloy sample and SEM images at various magnifications. The wavy region of the interface indicated as "good" weld.

Figure 4 represents the weld in progress in the configuration implemented here. The flyer material directly above the foil actuator is assumed to be launched flat and that whole section impacts at the measurement flyer plate velocity, V_P. In that region the impact angle, β, is zero due to which no welding is observed. However, rest of the flyer sheet trails behind and folds onto the target as the weld progresses to either side of initial impact region. The velocity of the flyer at a point located at a distance, x, from the foil actuator has a velocity of V_{Px}, which decreases with increasing x. It can be expected that there is a monotonically varying velocity gradient from region directly above foil actuator ($V_{P(x=0)}= V_P$) to the region below the standoffs ($V_{P(x=d)}=0$).
For low angles, V_w is related to flyer plate velocity and collision angle, β, as,

$$V_w = \frac{V_P}{\sin(\beta)} = V_F \qquad (1)$$

V_{Wx}, V_{Px}, and V_{Fx} would be related similarly. Therefore, it can be seen that V_{Fx} decreases as the weld progresses away from the initial impact region and as the impact angle increases.

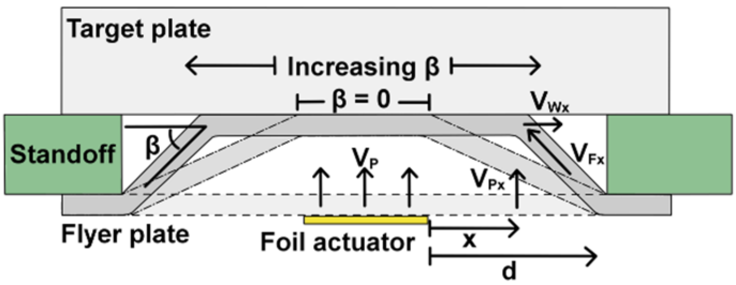

Figure 4: VFAW with the relevant configuration in progress

According to Eq. 2, due to Cowan et al. [12], for a constant Reynolds number, R_t, for a given pair, the welding velocity, V_w at which smooth-wavy transition happens is lower for a lower sum of hardness of the two materials. The lower bound or the smooth to wavy transition criteria is given by

$$R_{transition} = \frac{(\rho_{flyer}+\rho_{target})V_{F-transition}^{2}}{2(H_{flyer}+H_{target})} = K_{E-P} \tag{2}$$

Here ρ (kg/m^3) stands for density, V_F (m/s) for velocity of flow of the flyer material into the collision point, which approximately equals welding velocity, V_w for low collision angles. H represents Vicker's hardness (N/m^2). The smooth to wavy transition criteria depends on the hardness of two colliding members of the joint. If the sum of hardnesses is high, then the transition flow velocity, hence the transition welding velocity would also be high. Therefore smooth to wavy transition would happen at low values of β or x. Since the hardness of the target plate is quite high, it is not unexpected that the good weld region was very narrow.

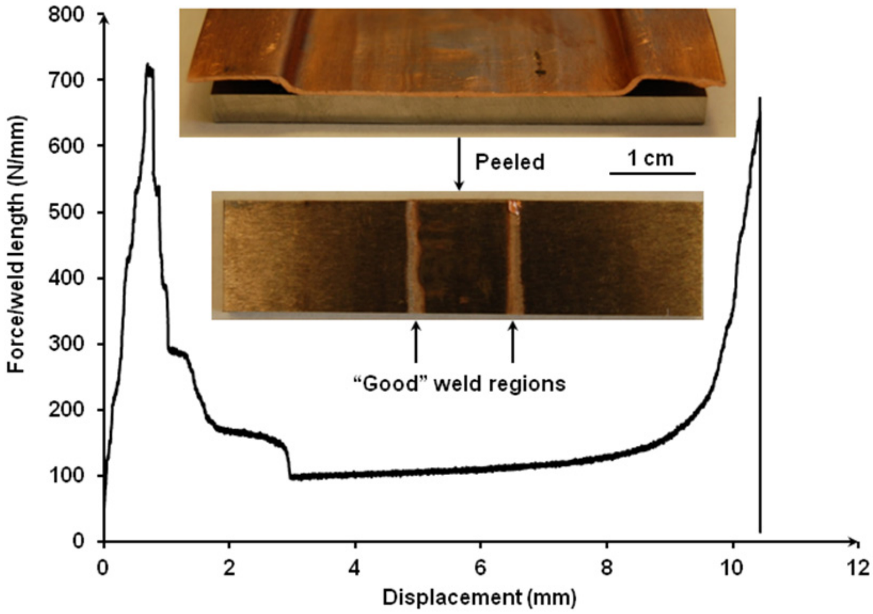

Figure 5: Peel test data showing two peaks corresponding to the two welded regions. The welded and subsequently peeled sample is shown inset in the figure.

The data from the peel test conducted on the welded sample is shown in Figure 5. The W-alloy side inset in the figure depicts, very clearly, the two bands along which optimal welding occurred. Accordingly there were two maxima in the force/weld length vs displacement plot. The peel strength was found to be nearly 60 N/mm.

The data obtained from the microhardness tests along the two lines across the interface is shown in Figure 6. The hardness of both Cu-110 and W-alloy were significantly higher than those of the original materials. Highest hardness for Cu side was found to be 129 HV while that on the W-alloy side was 483 HV. While the hardness generally increased monotonically as the interface was approached, it was found that along line A, the indent closest to the interface on the W-alloy side was larger and the hardness was measured as 382 HV. Further microstructural analysis is required to understand this anomaly.

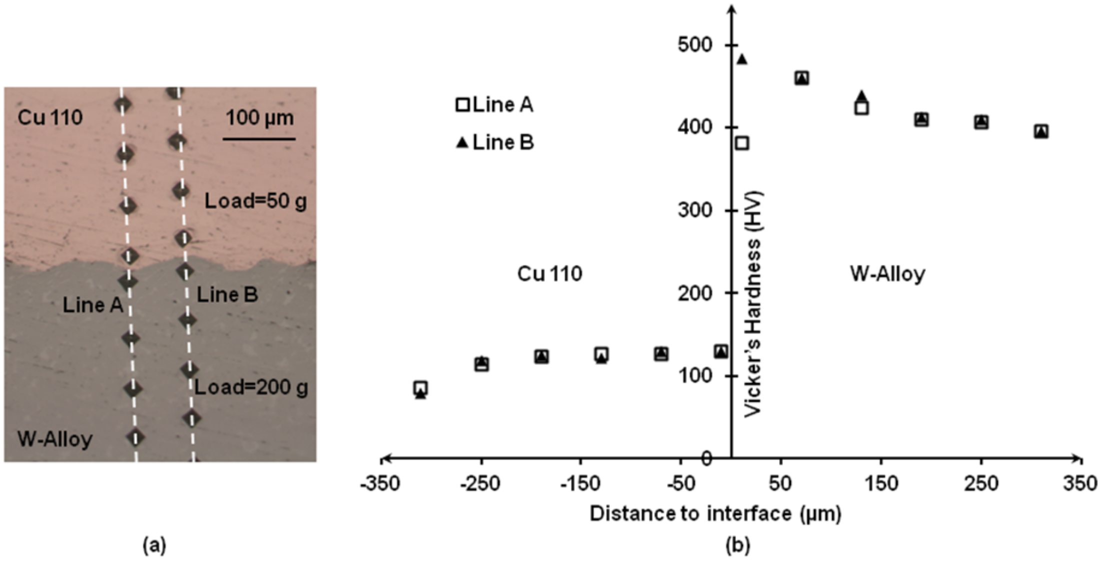

Figure 6: Microhardness tests. (a) post-test image of the Cu-110/W-alloy welded region showing the two lines along which tests were run, (b) A plot showing the variation of microhardness across the interface.

4. Conclusions

Based on this work, following conclusions can be drawn:

- It is possible to weld W-alloy 17D with copper using VFAW. The welded sample had significant peel strength of 58 N/mm.
- Since the aluminum foil is a consumable of each run, its longevity is not a concern while trying to increase the driving pressure. Impact velocity of nearly 550 m/s was attained within 1.6 mm of travel thereby indicating a very high driving pressure.
- It was found that the range of collision angle and velocity for which a good weld can be created between the copper and W-alloy is very narrow. This was verified against an analytical model, which indicated that the transition from a smooth to wavy interface occurs at higher welding velocities for combinations where either or both the materials in the welding couple are hard.
- Large amounts of plastic deformation on either side of the weld interface resulted in increased hardness as compared to parent materials. There was an anomaly on the W-alloy side where the hardness decreased near the trough of a wave.

Acknowledgements

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