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Inertial Weldment of Rhenium and Inconel 718

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March 2018

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS, ABBREVIATIONS, AND DESIGNATORS

BM	base metal
DMLS	direct metal laser sintering
EBW	electron beam weld
ED	Engineering Directorate
El-Form	electroform
EM32	Metallurgical Branch
ER23	In Space Propulsion Systems Branch
HAZ	heat-affected zone
MSFC	Marshall Space Flight Center
MTI	Manufacturing Technologies, Inc.
PI	principal investigator
PPL	Plasma Processes, LLC
SME	subject matter expert
WZ	weld zone

TECHNICAL PUBLICATION

INERTIAL WELDMENT OF RHENIUM AND INCONEL 718

1. INTRODUCTION

The desire for higher performance monopropellant thruster systems drives the development of high-performance propellant with much higher combustion temperatures. In turn, this desire for greater performance also drives the necessity for materials that can withstand these higher temperatures. This is one of the major technical barriers before the high-performance, low toxicity (commonly referred to as green) propulsion community. Refractory metals are ideally suited to this application, where high temperatures and oxidizing environment survivability is required. These materials are not without their detractors. The very properties that are sought are also those which make it difficult and costly to use. Nearly all refractory group metals are ill-suited for traditional fabrication techniques. They may require highly specialized fabrication techniques like powder metallurgy, chemical vapor deposition, or electroform (El-Form), but not all of the thruster must be made of these materials, only the areas that require them.

High temperature, long-life thruster chambers are being made using rhenium, a refractory metal with excellent high temperature performance. Rhenium chambers are usually coated with iridium, another refractory metal that serves as both an oxidation resistance cladding and a catalytic element. These metals are costly to form, compared to the more traditional super alloys that are common place in thrusters, such as Inconel 718. Because it is not necessary for all parts of a thruster to be manufactured from a refractory metal, it will be necessary to join those components to one of those alloys. A bolted joint, while possible, may not be an ideal solution. The disparity between the expansion coefficients of rhenium, Inconel 718, the bolt, and seal materials poses issues. Further, a bolted interface comes at a steep mass impact for small thrusters. A welded joint would be preferred for flight thrusters—the reason this study was commissioned.

NASA Marshall Space Flight Center's (MSFC's) In Space Propulsion Systems Branch (ER23) has built and tested several development thrusters of various thrust classes. In each case, the reactor is either bolted or threaded onto the injector and thermal standoff assembly. This is a feature that is necessary and helpful for the development thrusters; however, it is not necessary or desired for flight-rated thrusters. The genesis of this experiment was a NASA Innovative Kick-Start project, awarded to the principal investigator (PI) of this study, to build and test an additively manufactured 1N thruster. Direct joining of a rhenium reactor chamber to an additively manufactured thermal standoff and injector was identified early in trade studies as necessary to achieve a near flight weight thruster.

Fusion welding processes join materials of similar melting points and compositions. A literature review and inquiries with subject matter experts (SMEs) indicated that fusion welding methods would not be effective in joining rhenium and Inconel 718. ER23, in partnership with the Metallurgical Branch (EM32), began to review diffusion bonding as a means to join rhenium and Inconel 718 (fig. 1). The theorized process was to diffusion bond the two materials together and electrical discharge machine a transition ring that allows for electron beam welding a rhenium reactor to an Inconel standoff.

Three concepts (fig. 2) were drawn and discussed with an in-house SME about merit of the approach, feasibility of these concepts to fabricate test specimens, recommended alternative concepts based on experience and best practices, and to draft a scope of task and quote.

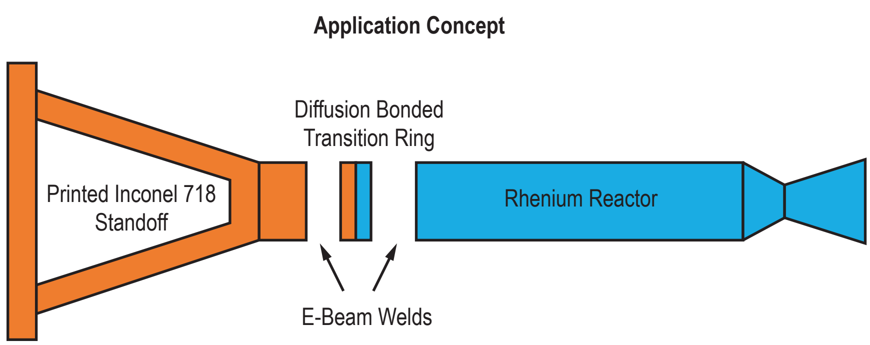

Figure 1. Original concept for joining rhenium and Inconel 718 for small thrusters.

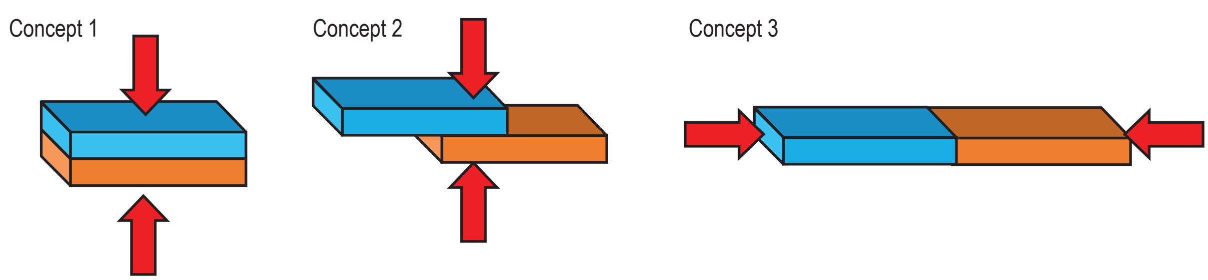

Figure 2. Diffusion bonding concepts originally explored.

Again, because the material properties' differences between the two, the diffusion bonding approach was abandoned. It was suggested that inertia welding might hold the key to success. Inertia welding is a form of friction welding in which parts are joined by driving a rotating part into another component that is held fixed in a collet (fig. 3). The heat and forces created by the friction allows plasticized dislocation motion to occur, thus generating additional heat and creating a very strong bond at the weld interface. A similar approach is applied in friction stir welding, a process that MSFC has a great deal of experience with. This process would potentially allow us to effectively and efficiently weld the two dissimilar metals.[3,4]

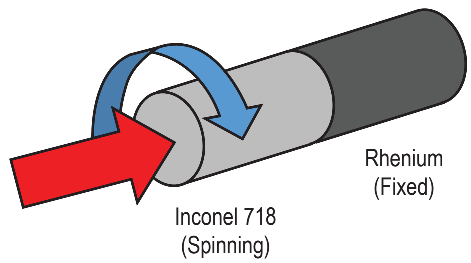

Figure 3. Illustration of inertia weld process.

ER23 and EM32 began to poll interested commercial vendors willing to conduct this exploratory study in joining rhenium and Inconel 718. Manufacturing Technologies, Inc. (MTI) expressed interest from a very early stage, and agreed to make public the data regarding the process parameters for the purposes of this publication. The goal of the study was simple—determine if inertia welding of rhenium and Inconel 718 holds promise for aerospace applications to warrant further investigation. MTI assisted NASA in designing the experiment and determining the dimensional specifications of the samples. Each sample would be 0.25 inch in diameter and 0.5 inch long. Standard dimensional tolerances were applied. NASA would provide 14 rhenium and additively manufactured Inconel 718 pins to be joined. Later in the experiment, solid Inconel 718 was used because tearing occurred in the additively manufactured Inconel 718 parts in early weld attempts. The basic plan was to allow MTI to attempt initial parameter exploration with up to five samples; then, MTI would build three samples at the initial parameter set. MTI would then vary one parameter (either speed or force-fixed flywheel mass) and build three more samples at the new parameters set. MTI would repeat this process to build a third set of three samples. MTI will leave all flashing on the samples. All samples would be delivered to MSFC for bend testing, sectioning, hardness testing, and macroscopic analysis.

This process was deemed as having the highest chance for success, and a Tech Excellence proposal was submitted and won. The MSFC Engineering Directorate (ED) awarded $7,500 to the ER23 PI for the study in November 2016. A NASA solicitation for the study was publically competed, but MTI was the only technically acceptable bid. MTI quotes that the study would cost $15,000. EM32 provided an additional $5,000 for the study, and ER23 provided an additional $2,500.

ER23 procured the rhenium samples from Plasma Processes, LLC (PPL) (fig. 4). The samples were manufactured using an El-Form process, and wire electrical discharge machined to final dimension. All samples were visually inspected, and found to meet the dimensional specifications for the study. The Advanced Manufacturing Branch printed 15 Inconel 718 samples per the dimensional specifications. The samples were hot isostatic pressed and heat treated per AMS5663.[3] The delivered samples were inspected and found to meet the dimensional specifications. All samples were shipped to MTI in February 2017. The additional solid Inconel 718 samples were shipped to MTI in May 2017.

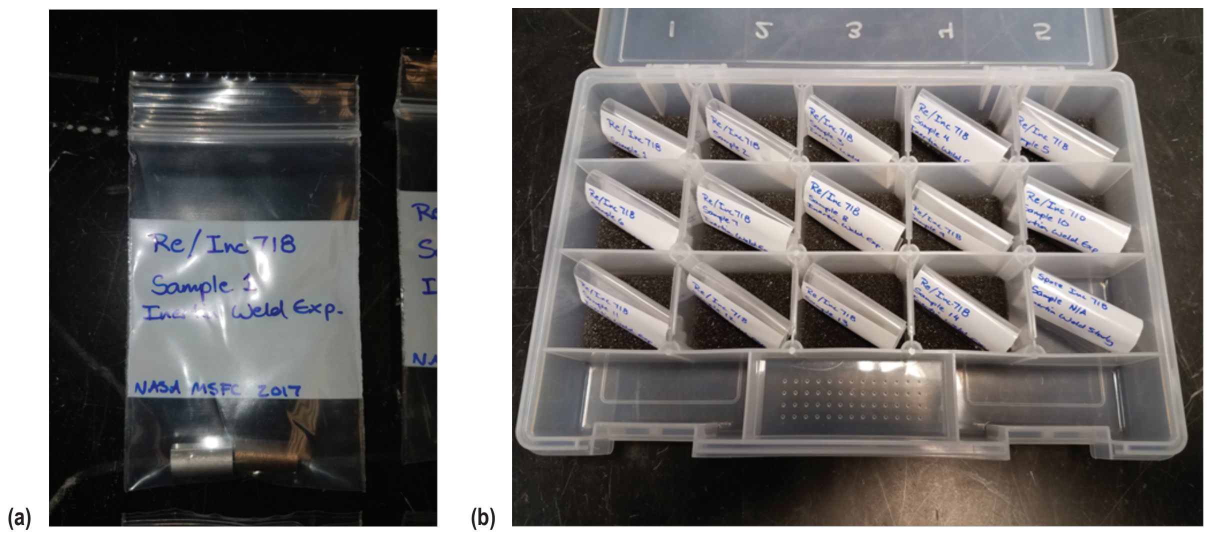

Figure 4. Rhenium samples: (a) Prepared samples and (b) sample kit.

Figure 5 shows one of the preweld samples. The specimen on the left is rhenium and the specimen on the right is Inconel 718.

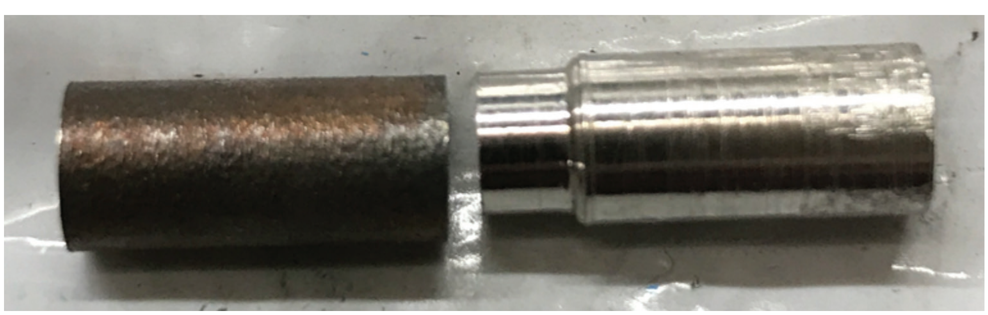

Figure 5. Preweld sample.

2. EXPERIMENTAL PROCEDURE

Kitted rhenium and Inconel 718 samples were sent to MTI for development of inertia welding parameters. The rhenium samples were fabricated by PPL using their El-Form process and wire electrical discharge machined to its final dimension. The Inconel 718 samples were printed using MSFC's EOS M 290 direct metal laser sintering (DMLS) machine. The samples were printed with the cylindrical axis aligned in the *z*-direction. All samples were initially 0.25 inch in diameter and 0.5 inch in length.

First, MTI polished the rhenium with 400 grit sandpaper and the Inconel 718 with 800 grit sandpaper to remove any oxide layers. Then, the samples were rinsed with acetone. In order to maintain a flat surface after polishing, they were held flat in a stationary position while the polishing wheel rotated. The rhenium was then placed flush within the inertia weld fixture and the Inconel 718 piece was inserted into the spindle. The initial fixture gap was set to 0.09 inch in order to maintain the gap tolerance of ±0.010 inch.

The first attempts to join rhenium and the printed Inconel samples produced weak bonds with tearing witnessed in the Inconel. This was later determined to be an interlaminar failure of the printed Inconel samples. The root cause was determined to be because the cylindrical axis of the samples was aligned in the *z*-axis of the printed samples. Additionally, cracking was observed in the rhenium. Due to the brittle nature of rhenium, it would crack rather than flash, like more ductile metals. New wrought Inconel 718 samples were sent to MTI. The rhenium was fully sunk into the collet to restrain it and prevent cracking. The weld joint diameter on the Inconel 718 side was decreased from 0.25 inch to 0.21 inch. This was done to allow the Inconel 718 to flash fully without interfering with the weld fixture.

The flywheel size, revolutions per minute, and weld pressure were the primary variables that were adjusted in order to achieve proper upset and a consistent weld interface. As welding parameters varied, the team at MTI performed basic metallography and bend testing to analyze mechanical failure. The metallography was done by using wire electrical discharge machining to cross section the weld and then by observing the weld cross section with an optical microscope. The welds were checked for consistency of the interface and the amount of flash. The opposing half of the weld cross section was used for bend testing. In order to conserve material, welds that were visually defective were cut apart and the opposite ends of the two parts were prepared and welded.

After nine welds, the parameters from the ninth weld were repeated because they exhibited the most consistent weld interface, and bend testing led to failure of the weaker of the two materials outside the weld interface. These parameters were repeated three times and then the revolutions per minute were varied slightly and repeated three times. Finally, the pressure of the ninth weld parameter set was varied and repeated twice. This resulted in three groups of welds that were returned to MSFC for analysis.

At MSFC, one full sample from each of the three parameter sets was bend tested to failure. Then the remaining weld(s) from each parameter set was cross sectioned using wire electrical discharge maching and polished for metallography. The weaker of two etchants for the two materials was used to etch the weld cross section and then the samples were imaged with an optical microscope. Finally, the samples were hardness tested across the weld interface to determine the hardness variation. The experimental matrix, including weld parameters, is shown in table 1.

Table 1. Inertia weld parameters used to generate the optimal weld interface and produce three sets of repeatable welds (welds 10–17/samples 7–14).

Spindle material: Inconel	Machine S/N: 06BHLF2929
Tailstock material: Rhenium	JO No.: 35104
Customer: NASA	Cylinder area: 2.403
Machine model: 60B	

Weld No.	Sample No.	Machine	Outer Diameter (in)	Weld Surface Area (in^2)	Total Inertial Mass Wk^2 ($lb\text{-}ft^2$)	Weld (rpm)	Weld Pressure (psi)	Surface Velocity (sfpm)	Total Energy E1t (ft-lb)	Total Load L1t (lb)	Specific Energy Es ($ft\text{-}lb/in^2$)	Specific Load L1s (lb/in^2)	Loss of Length or Upset (in)
1	1	60	0.248	0.048	0.2367	7,500	890	487	2,267	2,139	46,932	44,274.18	0.025
2	2	60	0.248	0.048	0.5767	5,550	1,020	360	3,025	2,451	62,616	50,741.20	0.08
3	3	60	0.248	0.048	0.2367	6,750	1,300	438	1,836	3,124	38,015	64,670.15	0.09
4	Reweld	60	0.21	0.035	0.2367	6,400	650	352	1,651	1,562	47,662	45,096.07	0.039
5	Reweld	60	0.21	0.035	0.1467	7,300	930	401	1,331	2,235	38,432	64,522.06	0.01
6	Reweld	60	0.21	0.035	0.2367	6,400	875	352	1,651	2,103	47,662	60,706.24	0.036
7	4	60	0.21	0.035	0.2367	7,400	930	407	2,207	2,235	63,720	64,522.06	0.043
8	5	60	0.21	0.035	0.5767	5,500	1,020	302	2,970	2,451	85,760	70,766.13	0.144
9	6	60	0.21	0.035	0.2367	7,500	1,020	412	2,267	2,451	65,453	70,766.13	0.069
10	7	60	0.21	0.035	0.2367	7,500	930	412	2,267	2,235	65,453	64,522.06	0.067
11	8	60	0.21	0.035	0.2367	7,500	930	412	2,267	2,235	65,453	64,522.06	0.075
12	9	60	0.21	0.035	0.2367	7,500	930	412	2,267	2,235	65,453	64,522.06	0.072
13	10	60	0.21	0.035	0.2367	8,000	930	440	2,579	2,235	74,471	64.522.06	0.077
14	11	60	0.21	0.035	0.2367	8,000	930	440	2,579	2,235	74,471	64,522.06	0.085
15	12	60	0.21	0.035	0.2367	8,000	930	440	2,579	2,235	74,471	64,522.06	0.082
16	13	60	0.21	0.035	0.2367	7,500	800	412	2,267	1,922	65,453	55,502.85	0.066
17	14	60	0.21	0.035	0.2367	7,500	800	412	2,267	1,922	65,453	55,502.85	0.055

3. RESULTS

Cracking was found in the rhenium in earlier samples and was decreased by decreasing the overall weld energy. This cracking was no longer observed in samples 7 through 14 which were returned to MSFC for testing.

Table 2 shows the hardness data for samples 7 through 14. Samples 1 through 6 were used to develop inertia weld schedules and procedures by MTI. The hardness values shown in table 2 are much higher than the raw hardness values of pure rhenium and Inconel 718 shown in table 3. This increase in hardness may be due to strain hardening. The hardness of the rhenium side of the weld samples tends to be greater than 350 Vickers which suggests that strain hardening greater than 100% occurred. The Inconel 718 side of the weld samples tends to have a hardness around 450 Vickers, suggesting that strain hardening led to about a 25% increase in the hardness of the Inconel 718. Inconel 718 and rhenium are known as two materials that exhibit a large amount of strain hardening potential. Rhenium is known as the material with the greatest potential for strain hardening, which explains why the hardness of the rhenium base metal in the inertia welded samples is much higher than that of raw pure rhenium.[3,6–8]

Table 2. Hardness values taken from samples 7 through 14.

Sample No.	Hardness (HV)	Location	Sample No.	Hardness (HV)	Location
7	532	Rhenium/base	11	317	Rhenium/base
7	324	Rhenium/base	11	335	Rhenium/base
7	337	Rhenium/base	11	336	Rhenium/base
7	410	Rhenium/base	11	343	Rhenium/base
7	337	Rhenium/base	11	313	Rhenium/base
7	342	Rhenium/HAZ	11	335	Rhenium/HAZ
7	405	Rhenium/HAZ	11	389	Weld zone (rh)
7	397	Weld zone (rh)	11	443	Weld zone (in)
7	471	Weld zone (in)	11	417	Weld zone (in)
7	386	Inconel 718/HAZ	11	375	Inconel 718/HAZ
7	383	Inconel 718/HAZ	11	408	Inconel 718/HAZ
7	431	Inconel 718/base	11	461	Inconel 718/base
7	415	Inconel 718/base	11	475	Inconel 718/base
7	445	Inconel 718/base	11	475	Inconel 718/base
7	417	Inconel 718/base	11	469	Inconel 718/base
8	404	Rhenium/base	12	415	Weld zone (in)
8	439	Rhenium/base	12	402	Weld zone (in)
8	386	Rhenium/base	12	349	Inconel 718/HAZ
8	400	Rhenium/base	12	394	Inconel 718/HAZ

Table 2. Hardness values taken from samples 7 through 14 (Continued).

Sample No.	Hardness (HV)	Location	Sample No.	Hardness (HV)	Location
8	377	Rhenium/HAZ	12	441	Inconel 718/base
8	429	Weld zone (rh)	12	442	Inconel 718/base
8	445	Weld zone (in)	12	448	Inconel 718/base
8	394	Inconel 718/HAZ	12	462	Inconel 718/base
8	369	Inconel 718/HAZ	12	452	Inconel 718/base
8	412	Inconel 718/base	12	462	Inconel 718/base
8	421	Inconel 718/base	12	442	Inconel 718/base
8	439	Inconel 718/base			
8	450	Inconel 718/base			
8	454	Inconel 718/base			
9	429	Rhenium/HAZ	13	324	Rhenium/base
9	327	Weld zone (rh)	13	330	Rhenium/base
9	325	Weld zone (rh)	13	276	Rhenium/base
9	368	Weld zone (in)	13	308	Rhenium/base
9	424	Weld zone (in)	13	335	Rhenium/HAZ
9	349	Inconel 718/HAZ	13	384	Weld zone (rh)
9	377	Inconel 718/HAZ	13	442	Weld zone (in)
9	422	Inconel 718/base	13	445	Weld zone (in)
9	446	Inconel 718/base	13	354	Inconel 718/HAZ
9	450	Inconel 718/base	13	380	Inconel 718/HAZ
9	454	Inconel 718/base	13	425	Inconel 718/base
			13	465	Inconel 718/base
			13	458	Inconel 718/base
			13	455	Inconel 718/base
			13	463	Inconel 718/base
10	386	Rhenium/base	14	353	Weld zone (rh)
10	374	Rhenium/base	14	336	Weld zone (rh)
10	383	Rhenium/base	14	412	Weld zone (in)
10	375	Rhenium/base	14	424	Weld zone (in)
10	310	Rhenium/base	14	381	Inconel 718/HAZ
10	387	Rhenium/HAZ	14	355	Inconel 718/HAZ
10	328	Rhenium/HAZ	14	422	Inconel 718/HAZ
10	444	Weld zone (rh)	14	460	Inconel 718/base
10	438	Weld zone (in)	14	464	Inconel 718/base
10	438	Weld zone (in)	14	464	Inconel 718/base
10	368	Inconel 718/HAZ	14	460	Inconel 718/base
10	402	Inconel 718/HAZ	14	464	Inconel 718/base
10	459	Inconel 718/base	14	450	Inconel 718/base
10	468	Inconel 718/base	14	441	Inconel 718/base
10	433	Inconel 718/base			

Table 3. Pertinent material properties for pure rhenium and Inconel 718.[1,2]

	Rhenium	Inconel 718
Hardness	85 HRB = 170 HV	~30HRC = 350 HV
Tensile strength	155 ksi	185 ksi
Modulus of elasticity	68,000 ksi	29,000 ksi

3.1 Bend Testing Method

Welded samples were fixed in a bench vice. An adjustable jaw wrench was tightened onto the sample (fig. 6). A bend load was applied manually until the sample broke. The objective was to apply a load until the sample broke, then observe where the joint failed. If the sample broke fully in the weaker or more brittle of the two materials, in this case the rhenium, it is evidence of a good weld.

Figure 6. Sample being bend tested.

3.2 Bend Testing Images

Figure 7 shows various bond test samples after welding.

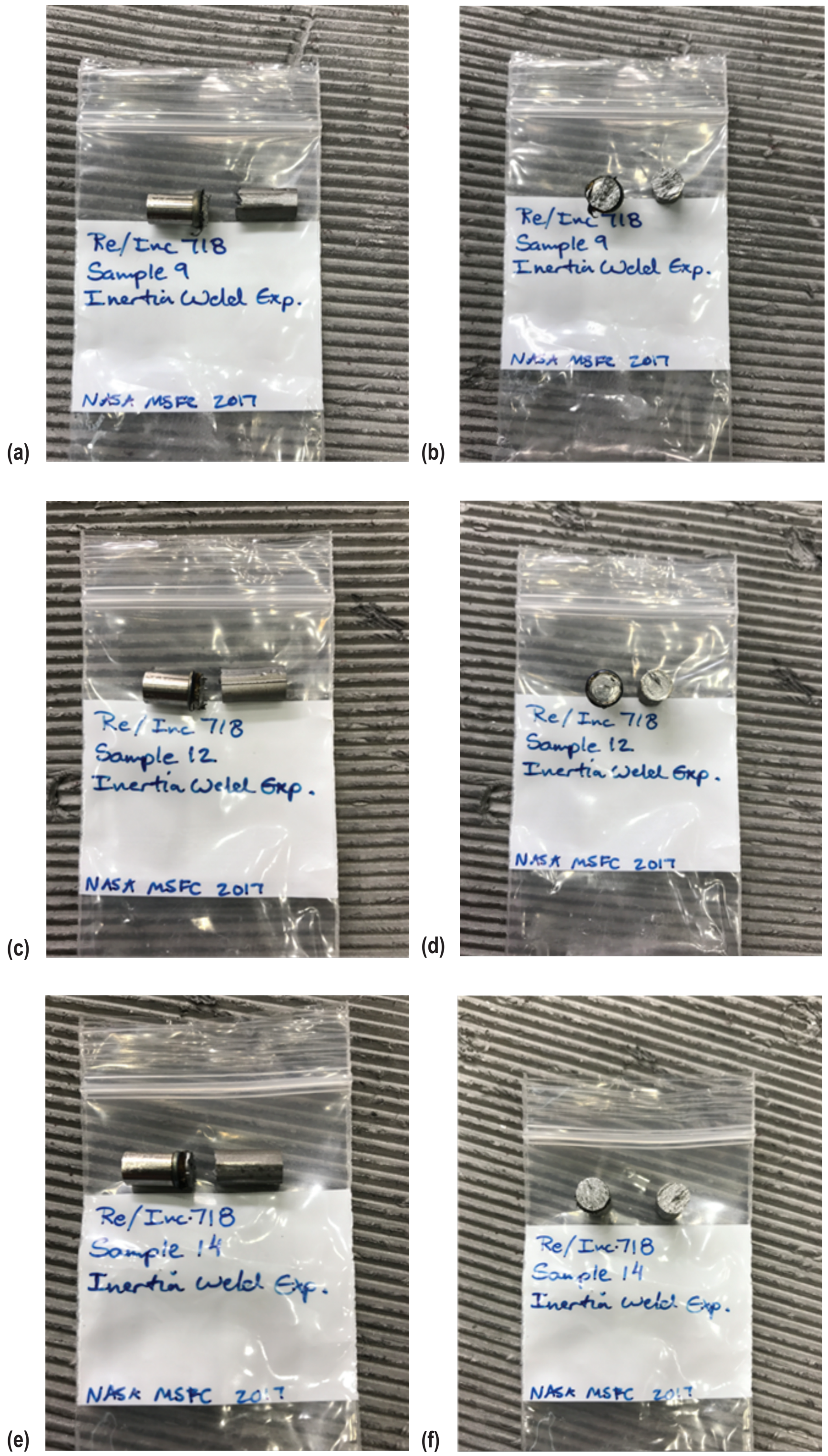

Figure 7. Bend test samples after welding: (a) Sample 9 side view, (b) sample 9 end view,[2] (c) sample 12 side view, (d) sample 12 end view,[2] (e) sample 14 side view, and (f) sample 14 end view.

Figure 8 shows the cross sections of the rhenium/Inconel 718 welds just prior to microhardness testing. It shows screenshot images of the cross sections with the locations of the microhardness tests. Sample 8 was imaged with an optical microscope in figure 8 in order to show the hardness test locations. The tests were conducted in a straight line across the weld interface from left to right and samples 12 and 14 have one test taken in the base metal far from the weld interface. This was done to determine if hardness varied greatly from just outside the heat-affected zone (HAZ) to the end of the base material. It was found that the difference in hardness for sample 12 base metal tests 5 through 11 maintained a hardness range between 440 and 465 Vickers. This finding was also confirmed for sample 14 base metal tests where the hardness was also between 440 and 465 Vickers. The Inconel 718 base metal tests far from the weld zone both had a modest drop in hardness while remaining within the 25 Vickers range established by the other Inconel 718 base metal tests, as shown in table 3. This may be because the strain just outside the HAZ is the highest strain that the material experienced and further from the weld zone, the strain hardening affect may have decreased slightly. Samples 9, 12, and 14 shown in figure 8 were bend tested to failure prior to metallography so only the side of the sample with the weld present was imaged.

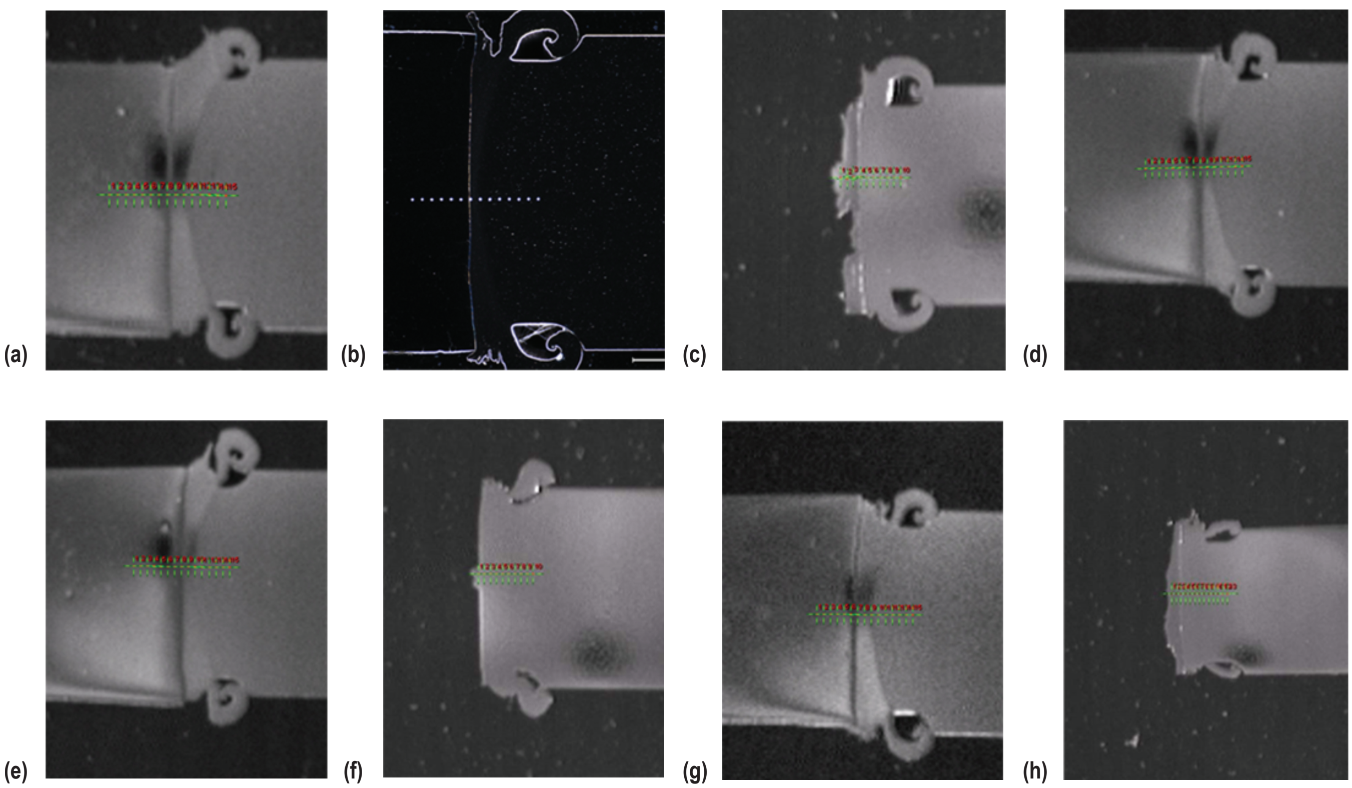

Figure 8. Locations of hardness tests along the cross section of rhenium/Inconel 718 welds: (a) Sample 7, (b) sample 8, (c) sample 9, (d) sample 10, (e) sample 11, (f) sample 12, (g) sample 13, and (h) sample 14.

The images in figure 9 shows samples 7 through 14, three of which were bend tested prior to metallography and the remaining five samples were bend tested after metallography and hardness testing. Sample 11 clearly shows deformation of the rhenium base metal which may have been caused by the high loads experienced during inertia welding. This deformation was much more clearly observed in the rhenium base metal because rhenium has a modulus of 68,000 ksi while Inconel 718 has a modulus of 29,000 ksi, according to table 3. This clear deformation proves that the rhenium base metal was under strain during welding which may have led to a large amount of strain hardening.[3,7–8]

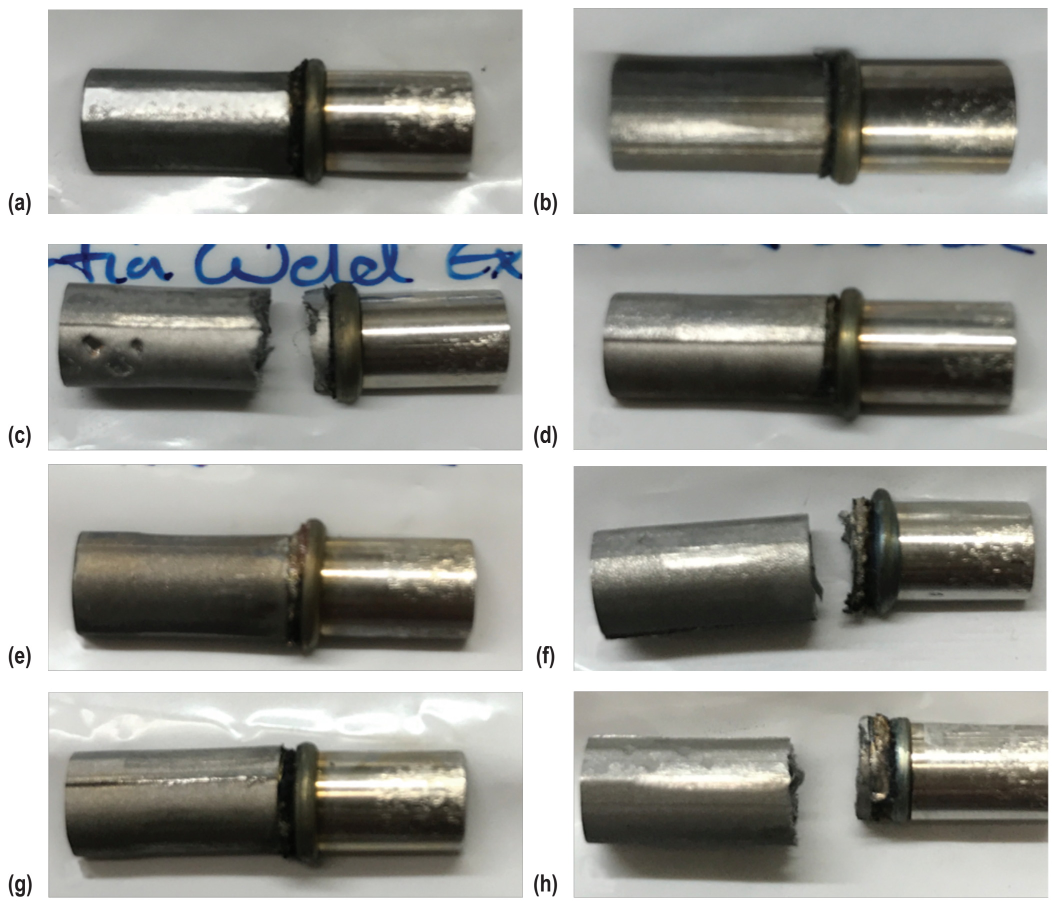

Figure 9. Images of rhenium/Inconel 718 inertia welds: (a) Sample 7, (b) sample 8, (c) sample 9, (d) sample 10, (e) sample 11, (f) sample 12, (g) sample 13, and (h) sample 14.

Figure 10 shows optical images of the weld cross sections for samples 7 through 14. Samples 9, 12, and 14 only show the Inconel 718 side of the weld with what was left of the rhenium portion of the weld after bend testing to failure. Samples 9 and 14 still have the majority of the rhenium portion of the weld intact, thus proving that the weld failed within the rhenium HAZ. According to table 3, rhenium has lower tensile strength than Inconel 718 so a failure in the rhenium HAZ proves that the weld is stronger than the weaker of the two materials. This is a major criteria for the success of a dissimilar weld. Sample 12 failed partially in the rhenium and primarily down the bond interface suggesting that the parameters used for sample 12 may not be optimum.[9]

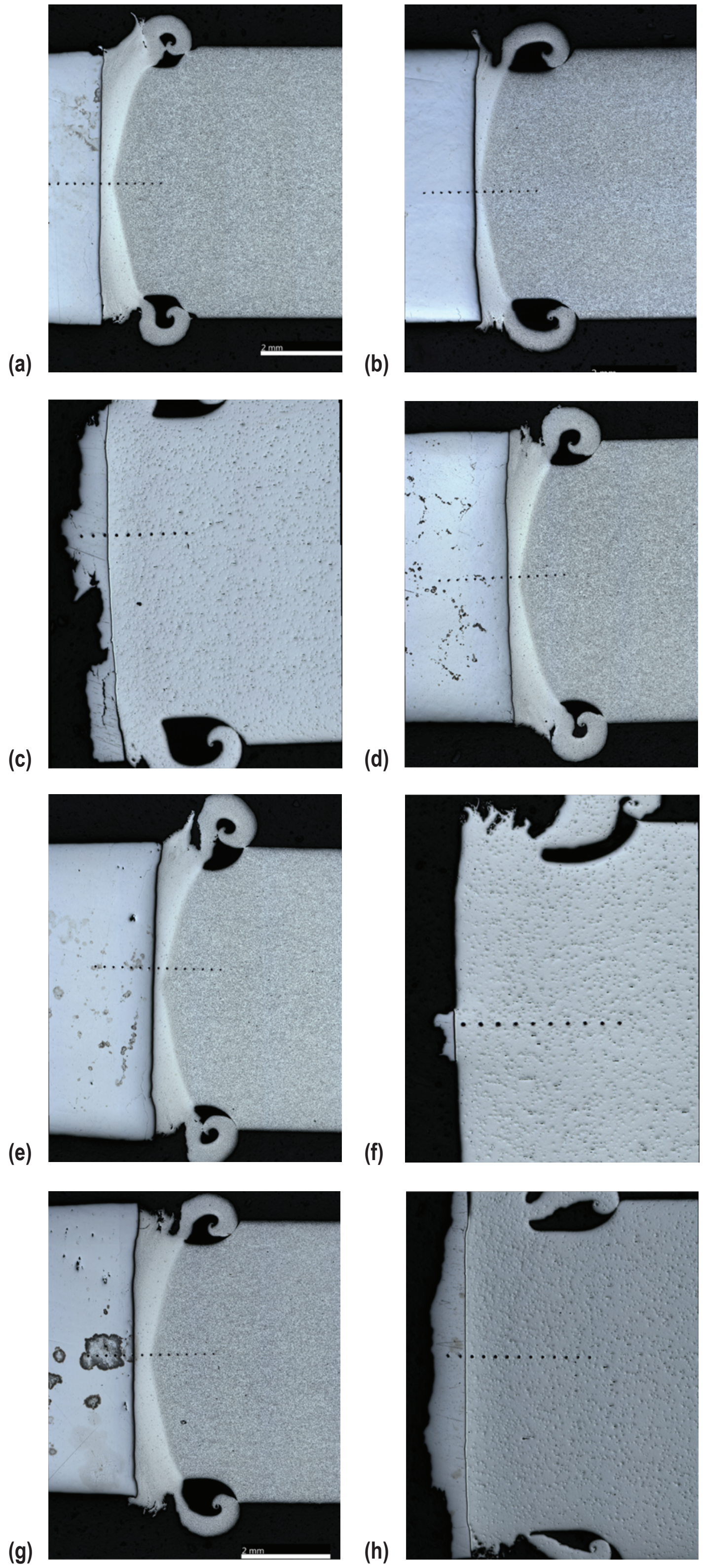

Figure 10. Macrographs of rhenium/Inconel 718 inertia welds at ×200 magnification: (a) Sample 7, (b) sample 8, (c) sample 9, (d) sample 10, (e) sample 11, (f) sample 12, (g) sample 13, and (h) sample 14.

According to table 1, samples 7, 8, and 9 were made with 7,500 rpm and 930 psi; samples 10, 11, and 12 were made with 8,000 rpm and 930 psi; and samples 13 and 14 were made with 7,500 rpm and 800 psi. The images of samples 7 and 8 in figure 10 show consolidated welds with only slight surface defects. No internal cracks, voids, or material breaking away was observed in samples 7 and 8. Sample 9 was bend tested and the failure occurred 100% in the rhenium base metal. The portion of the weld where both the Inconel 718 and rhenium initially came into contact remained consolidated during bend testing and the weld interface opened in the flashing region of the weld. Samples 10 and 11 also appeared consolidated but contained some HAZ cracking. During bend testing, sample 12 failed mostly along the weld interface, indicating a weak weld bond. Materials were limited so the third set of inertia welding parameters was only used to make samples 13 and 14. Sample 13 showed a consolidated weld interface free of any clear defects. Any defects were observed in the flash of the weld which would be removed in any application and the interface where the two different parts initially came together was completed consolidated. Sample 13 was bend tested and failed completely within the rhenium base material. Unlike sample 9, sample 13 exhibits an even failure region without any cracking occurring closer to the weld. This proves that the weld interface was stronger than the rhenium base material along the entire weld. Samples 7, 8, 10, and 11 all exhibit slight defects in the rhenium side of the weld joint where crack propagation may occur. Therefore, the inertia weld parameters used for samples 13 and 14 appear to display the most ideal results.[9]

After metallography and microhardness testing, the remaining cross-section portions of samples 7, 8, 10, 11, and 13 were bend tested to failure. Doing this helped obtain the maximum amount of data from the limited amount of weld tests performed. Bend testing was performed in a way to ensure that the internal cross section was in tension while the exterior of the weld was in compression. Samples 7, 8, and 11 all failed within the rhenium HAZ, sample 13 failed mostly in the rhenium HAZ, and a small portion of the samples failed along the weld interface. Sample 10 failed along the weld interface and partially within the rhenium HAZ like sample 12 shown in figure 10. This suggests that the parameters used for samples 10 through 12 do not produce a dissimilar weld with strength greater than the weaker of the two materials. The parameter sets used for samples 7 through 9, 13, and 14 both appear to produce welds with greater strength than the rhenium base material. The parameter set for samples 13 and 14 appears crack free, suggesting that those parameters were better than the other parameter sets. Further experimentation is necessary to determine which parameter set is optimal and to further refine the optimal parameter set.

4. DISCUSSION

Figure 11 displays the hardness testing data across the weld zone (WZ) starting from the rhenium base metal on the left and ending with the Inconel 718 base metal on the right.

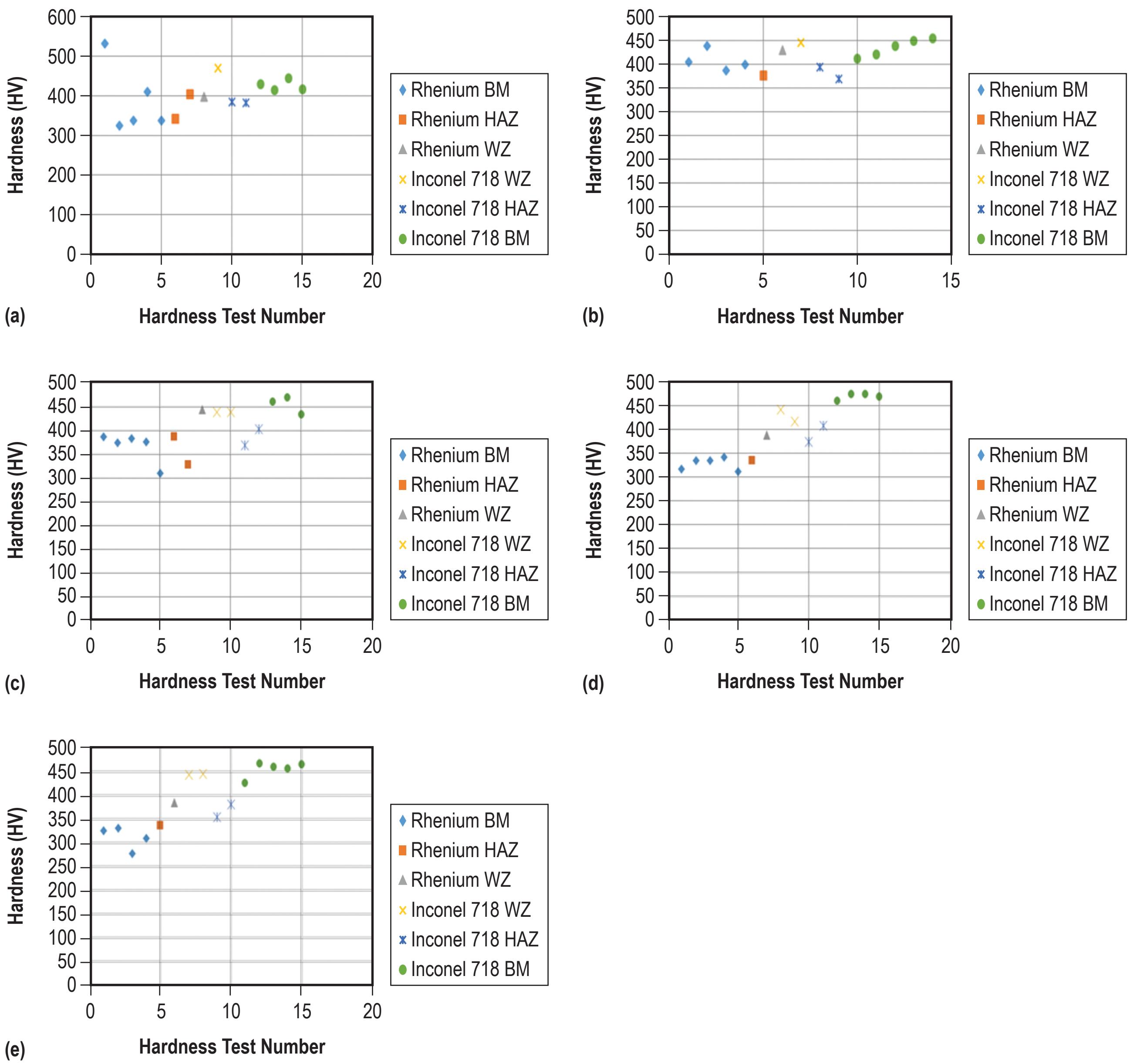

Figure 11. Graphs of microhardness tests for individual inertia welds that were not bend tested: (a) Sample 7, (b) sample 8, (c) sample 10, (d) sample 11, and (e) sample 13.

Samples 7 and 8 were made with one set of parameters, 10 and 11 were made with a second set of parameters, and sample 13 was made with its own set of parameters that are shown in table 1. Samples 7 and 8 show relatively consistent hardness across the weld interface with a spike in hardness in the rhenium base metal and the Inconel 718 weld zone. Samples 10 and 11 display a greater variation in hardness with the Inconel 718 base metal exhibiting the highest hardness.

The hardness of raw rhenium is 170 Vickers and the hardness of Inconel 718 is around 350 Vickers according to table 3. The Inconel 718 exhibits a consistent drop in hardness in the HAZ which may be attributed to a loss of the heat-treated condition inherent to Inconel 718. While its hardness decreased, it still remained above the hardness of as-produced Inconel 718 which may be due to strain hardening. The rhenium exhibits a hardness greater than 300 in all of the sample graphs shown in figure 11 except sample 13, where one hardness test was 276 Vickers. Since these hardness values are far greater than 170 Vickers, it can be ascertained that strain hardening led to an increase in hardness of the rhenium. Since the unwelded rhenium was pure and did not go through any heat treatments, there was no consistent loss of hardness from the rhenium base metal to the rhenium HAZ. Inertia welding induces great strain on the parts being welded, which suggests that strain hardening could have occurred. Samples welded with identical parameters appear to maintain consistent hardness profiles, thus suggesting that inertia welding of pure rhenium to Inconel 718 is a repeatable process.[3,6–8]

The graphs shown in figure 12 separate the hardness data of the rhenium side of the weld from the hardness data of the Inconel 718 side of the weld. The rhenium hardness data are relatively consistent and have a slight decrease in hardness as distance from the weld zone increases. The hardness of the Inconel 718 HAZ is consistently lower than that of the Inconel 718 weld zone and base metal. This may have been caused by a loss of the heat treated condition and does not decrease the hardness below 349 Vickers as seen in table 2. Overall, the hardness testing data are consistent among each set of parameters and hardness in each region of the weld does not vary greatly between welds 7 through 14. Rhenium base metal hardness appears to increase slightly further from the HAZ according to figure 12.

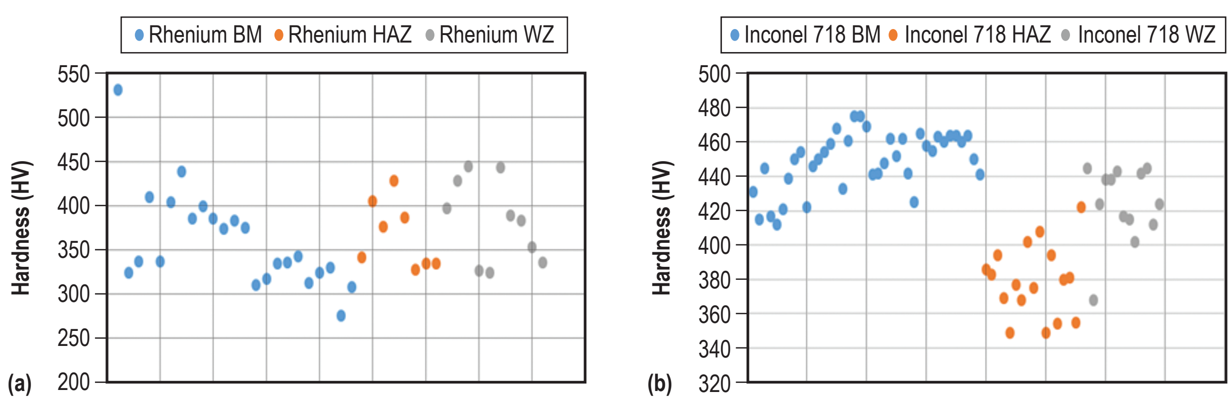

Figure 12. Graphs of all hardness testing data: (a) Rhenium and (b) Inconel 718.

Samples 1 through 14 were all welded by MTI and samples 7 through 14 were shipped to MSFC for testing and inspection. The first six weld samples were used to generate welding parameters that create a weld free of defects with consistent flash. MTI performed metallography and bend testing on the first welds they found which were consolidated. Once they determined parameters which generated visually defect-free welds, they repeated and varied those parameters to make samples 7 through 14.

5. CONCLUSION

The weld parameters used to weld samples 7 through 9 and 13 and 14 were both found to produce a stronger weld than the parameters used to weld samples 10 through 12. Both optimal parameter sets produced welds with greater strength than the rhenium which was determined by bend testing to failure. The parameters used for samples 13 and 14 may be more ideal because the welds it produced did not exhibit cracking in the rhenium while all other welds had minor cracking in the rhenium. Both materials experienced strain hardening; the rhenium strain hardened to increase its hardness by greater than 100% and the Inconel 718 had an increase in hardness around 25%. These hardness values varied but were consistently greater than that of the raw materials.[3,7–8]

The Inconel 718 experienced a drop in hardness within the HAZ which may be attributed to a loss of the heat-treated condition due to heat from the inertia weld. The hardness of the Inconel 718 base metal then increased above the hardness found within the Inconel 718 side of the weld zone due to low heat and high strain caused by the friction and forging forces inherent to inertia welding. The rhenium side of the weld did not experience a loss of hardness in the HAZ which may be due to the fact that it was not heat treated prior to welding. The hardness of the rhenium decreased with distance from the weld zone which may be attributed to higher strain rates closer to the weld zone. The rhenium hardness increased slightly further into the base metal which may have been caused by decreased heat conduction and high strain in that region.[3,6–8]

Overall, inertia welding has great potential for joining pure rhenium to Inconel 718. The geometrical limitations of inertia welding make it so this process is best utilized to make a round transition joint so homogeneous welds can be made for the rhenium and Inconel 718 sides of the weld joint. Further experimentation is necessary to determine the tensile strengths and other material properties of rhenium/Inconel 718 inertia weld joints through mechanical and nondestructive testing.

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14. ABSTRACT
Inertia welding has been found to be a successful method for joining pure rhenium to Inconel 718, and with additional experimentation, this process may have great potential for rocket nozzle applications. Refractory metals are ideally suited to this application, where high temperatures and oxidizing environment survivability is required, but not all of the thruster must be made of these materials, only the areas that require them. A bolted joint between the two metals is not ideal, especially for small thrusters where the mess of a bolted join will come at a steep price. A welded joint would be preferred for flight thrusters.

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rhenium, Inconel 718, inertia, welding, joining, refractory

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