

Pulsed Magnetic Welding for Advanced Core and Cladding Steels

Reactor Concepts R&D

Dr. Guoping Cao

University of Wisconsin-Madison

In collaboration with:

University of Florida

William Corwin, Federal POC

Stu Maloy, Technical POC

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1500 Engineering Dr.
Madison, WI, 53706

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Principle Investigator: Guoping Cao, gcao@wisc.edu

Working Partners: Sindo Kou, University of Wisconsin, kou@engr.wisc.edu
Yong Yang, University of Florida, yongyang@ufl.edu

Project objectives: To investigate a solid-state joining method, pulsed magnetic welding (PMW), for welding the advanced core and cladding steels to be used in Generation IV systems, with a specific application for fuel pin end-plug welding. As another alternative solid state welding technique, pulsed magnetic welding (PMW) has not been extensively explored on the advanced steels. The resultant weld can be free from microstructure defects (pores, non-metallic inclusions, segregation of alloying elements). More specifically, the following objectives are to be achieved. 1) To design a suitable welding apparatus fixture, and optimize welding parameters for repeatable and acceptable joining of the fuel pin end-plug. The welding will be evaluated using tensile tests for lap joint weldments and helium leak tests for the fuel pin end-plug. 2) Investigate the microstructural and mechanical properties changes in PMW weldments of proposed advanced core and cladding alloys. 3) Simulate the irradiation effects on the PWM weldments using ion irradiation.

1. Executive Summary

The major accomplishments of this project are follows.

- A comprehensive combination of advanced F/M steels including NF616, ODS, HT9, T91 and HT-UPS was studied in this project.
- The PMW process was optimized through modifying the parameters, including current and energy of welding coil, surface finish and geometry of the welding parts.
- Regarding the shape of pin end plug, large taper angle provides a longer acceleration distance and a resulted higher impact velocity. The welds on large taper angle plug have a much lower or nearly zero helium leak rate.
- Tensile tests show that the welding bond can have a similar strength with the base metal, particular for the HT-UPS.
- Both the optical and TEM images clearly shows that the width of the welding line in NF616 tube/plug welds is in the order of several micrometers. And this is significant smaller than those from TIG, e-beam, laser or other conventional fusion welding.
- The ion irradiation results show that the pulsed magnetic welding has a minimal or no effect on the irradiation response of the base materials.

Overall, it has been successfully demonstrated that the pulsed magnetic welding can be a potential solid welding technology for the tubular parts made from advanced F/M steel.

2. Project background

The primary goal of advanced fuel cycles is to expand the use of nuclear energy while mitigating the risk of nuclear weapons proliferation and ensuring safe nuclear waste disposal. These goals are to be met through the development and use of advanced technologies for recycling spent nuclear fuel paired with advanced burner reactors that consume transuranic elements from recycled spent fuel. Economical operation of advanced burner reactors requires structural and core materials that operate at higher temperatures than achieved in previous sodium-cooled fast reactor development programs. These higher temperatures, combined with high neutron fluxes, constitute a challenging environment for cladding and core structural materials. Since traditional austenitic stainless steels exhibit excessive radiation-induced void swelling at doses significantly lower than required for fast reactor cladding at the desired fuel burnups, material development programs shifted to ferrite/martensitic steels, and there are significant developments to further improve the high temperature strength of F/M steels during the last four decades. As one of the third generation of F/M steels, **NF616** has increased high temperature strength over T91 (second generation F/M steel) by partially substituting W for Mo and adding boron. Another method for improving the strength of F-M steels is through the addition of fine nanometer-sized oxide particles; the oxide dispersion-strengthened steels (**ODS**) with 9 Cr and 14 Cr have been developed by JAEA and ORNL, respectively. In addition to improving F-M steels, the swelling resistance and high temperature strength of an austenitic steel can be improved through the inclusion of high density of nanometer-sized precipitates such as those in the ORNL High Temperature Ultrafine-Precipitation-strengthened Steel (**HT-UPS**), which is also being evaluated for advanced burner reactor use. However, a potential issue that directly affects the application of advanced steels for core or cladding application is the change in properties associated with welding. Since the superior properties depend on the uniform tempered martensitic microstructure for F/M steels and evenly distributed nano-sized oxide particles and precipitates for ODS and HT-UPS respectively, any microstructural disruptions induced by welding may be deleterious. Developing welding techniques that limit microstructural alteration is critical. This issue presents a major challenge as improper welding or filler can seriously degrade the high temperature and swelling resistance properties of the material and eventually caused failures in the field.

Pulsed Magnetic Welding (PMW) is ideal for sealing fuel pin end-plugs as first demonstrated in Russia in the late 1960s. 316SS and Ni-base alloys such as Inconel 706 in the form of a tube were welded to an end plug machined from the same materials at Westinghouse Hanford (Brown et al, 1978) [1]. Recently, welding using PMW on ODS MA957, 956 and PM 2000 was tried by PNL (Pacific Northwest Laboratory) and JRC-ITU (Joint Research Center-Institute for Transuranium Elements) [2, 3] with promising results. As illustrated in Figure 1, in PMW an intense magnetic field is suddenly created through an instantaneous discharge of a large electrical current into a coil (e. g., 2 million amperes in 100 microseconds). An eddy current is induced in the outer tube in the opposite direction to create an opposing magnetic field. This creates a magnetic field pressure to accelerate (e.g., to 300 m/s) and collapse the outer tube, welding it to the inner tube. Joining is achieved in a fraction of a second without melting or excessive heating of the base metal near the weld, thus minimizing damage to the workpiece material. Figure 2 shows the welding of a cladding tube to an end plug by MPW [1].

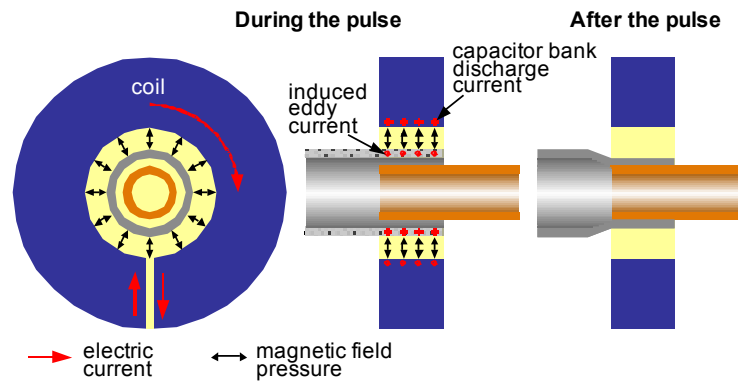


Figure 1 Pulsed magnetic welding of outer tube to inner tube (redrawn after Hirotec America, Auburn Hills, MI).

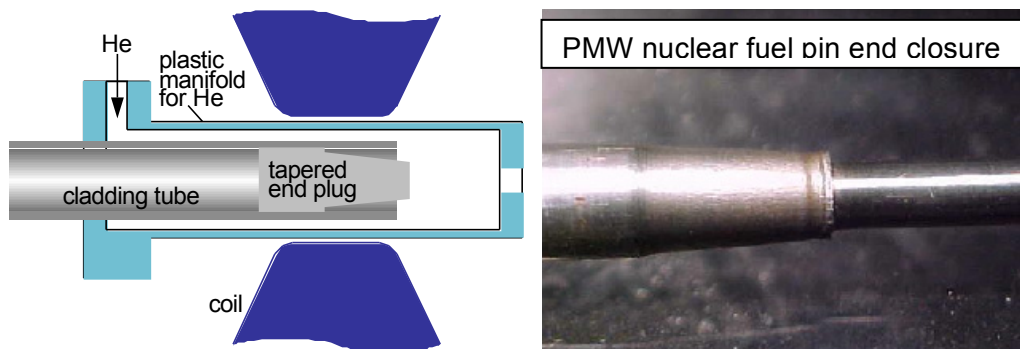


Figure 2 Pulsed magnetic welding of outer tube to end plug: (a) longitudinal cross-section (redrawn); (b) typical weld [1].

Irradiation effect on weldments:

The pre-irradiation microstructure can affect irradiation-induced defect formation, leading to not only a change of yield stress but also a change of the dominant deformation mechanism and fracture mode. Radiation-induced hardening, local chemical composition change, swelling and radiation creep must all be considered in the welding process design. Bae [4] studied the effect of electron irradiation on the microstructural damage in the welded portion of a SUS304 weldment. It was observed that the void size, void number density and void swelling in the HAZ were larger than those in the base material, possibly due to enhanced void nucleation in the HAZ. The width of the segregation profile of elements at grain boundaries in the HAZ was also slightly different from that of the base metal, which was postulated to be related to the void structures, and may cause different corrosion or crack growth rates. For JFMS (Japanese Ferritic-Martensitic Steel) welded joints, Kaga observed strong radiation embrittlement [5]. Morgan found significant microstructural variations in the irradiated weldment of FV448 with coarse martensitic laths partially transformed into austenite across the central weld metal zone, resulting in a duplex two-phase structure and a high level of radiation-induced voids present within the austenite grains, as illustrated in Fig. 3 [6]. Based on above reported works on irradiated effects on weldments, it appears that the microstructural response of weldments to irradiation can be extremely complex due to

the heat input, phase transformations, grain-size changes, local solute segregation and residual strain during welding.

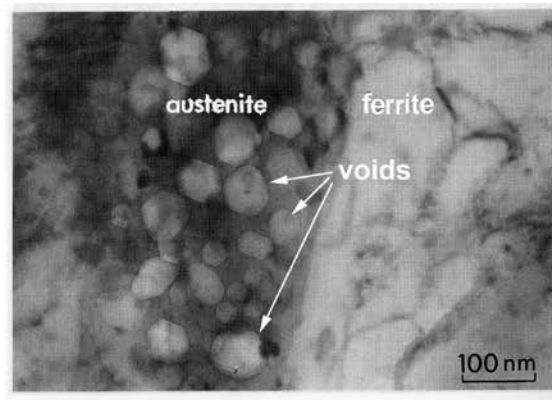


Figure 3 TEM image of transformed duplex austenite/ferrite structure in the irradiated weldment of FV447 [6].

The effect of radiation on PMW weldments has not been evaluated for the F/M, HT-UPS or ODS steels proposed as the fuel cladding material. As described in the PMW of 316 stainless steel by Brown [1], a typical bonded joint usually contained isolated melt pockets and the grains along the joint were heavily deformed. The bonded joint, as well as the affected base metal nearby, may respond to irradiation differently from the base metal far away. For HT-UPS and ODS steels, especially, the size and distribution of MC and oxide nanoparticles in the weld zone may respond differently from those outside. The void swelling and dislocation evolution near the bonded joint may differ from those away from it due to the pre-irradiation dislocation structures and precipitates distributions. This microstructural response may significantly affect the weld properties, such as the tensile strength, fracture toughness and crack development.

3. Major Accomplishment

The following sections describe the major accomplishments or outcomes in this project. They are presented in a form that focuses on the key results and conclusions. Details of the experiments and full set of results are available in the quarterly reports and are referenced herein rather than repeated.

Materials Procurement

Due to the fact that none of the advanced cladding materials is commercially available, a significant effort was carried to obtain the proposed materials by working closely with individual vendors or national laboratories. The 9 Cr ODS was obtained from Japan, and the HT-UPS steels were provided by ORNL after the project PI closely worked with the ORNL researcher on the material processing including hot rolling and heat treatments.

Table 3.1 Summaries of Materials.

Steel Type	As-received Form	Dimensions	Materials Condition	Welding work pieces
9 Cr ODS	Plate1	373mmx35mmx11mm	Extruded, hot forged, cold rolled and heat treated (1323K x 1h and 1073K x1h)	20 Thin plates (100mmx35mmx0.5mm) 20 Tubes (OD 5.85±0.05mm, ID 5.01±0.05) 20 Pins (Dia 5.85±0.05 L 30mm, and subject to final shaping)
	Plate 2	307mmx35mmx11mm		
NF 616	Section of thick pipe (1.66”T)	~110mmx42mmx~84mm	Rolled, heat treated (1300Kx2h air cooling, 1070Kx2h air cooling)	10 Thin plates (100mmx50mmx0.5mm) 10 Tubes (OD 5.85±0.05mm, ID 5.01±0.05) and 10 pins (Dia 5.85±0.05 L 30mm, and subject to final shaping)
T91*	4 PCs of plate	4”x2”x1”	From American Alloy Steel (Heat 60473), hot rolled and heat treated	50 Thin plates (100mmx50mmx0.5mm) 36 Tubes (OD 5.85±0.05mm, ID 5.01±0.05) and 42 pins (Dia 5.85±0.05 L 30mm, and subject to final shaping)
Ht9	Hex Duct	1.25” facet and 1/16” wall thickness, 10” in length	EBR-II duct, extruded and heat treated (1320Kx0.75h and 1050Kx2.5h)	6 Thin plates (100mmx30mmx0.5mm)
	3 PCs of Cladding tube	5.85mm OD, 0.42 wall thickness, 40” length	EBR-II cladding and extruded.	30 Tubes (OD 5.85)

HT-UPS	2 plates	13"x2.5"x0.024"	Hot-rolled rolled	6 Thin plates (100mmx50mmx0.5mm)
	Small block	2"x2"x0.5"	Extruded	4 pairs of tube/plug
SS 316	Plates, tubes and plugs for practicing purpose			

Welding experiments

Two major welding campaigns were performed on those materials with two sets of different designs.

Welding campaign #1

Table 3.2 summarizes the welding matrices for the welding campaign #1, it can be seen that both tube and lap welding were included, and the dissimilar welding between ODS, NF616 and HT-UPS were also planned.

Table 3.2 Welding matrices for campaign #1.

Tube/Plug welding	Tube	Plug	Final Delivery	Practicing on:
1	HT-9	T91	3 pcs	T91/HT9 tube
2	NF616	NF616	3 pcs	T91/HT9 tubes
3	HT-UPS	HT-UPS	3 pcs	316 SS
4	ODS	ODS	3 pcs	T91 plug/HT9 TUBE
5	ODS	NF616	3 pcs	T91 plug/HT9 Tube
6	ODS	HT-UPS	3 pcs	T91/316SS
Lap welding	PC #1	PC#2		
7	NF616	NF616	3 pcs	T91
8	HT-UPS	HT-UPS	3 pcs	CW 316 SS
9	ODS	ODS	3 pcs	T91
10	HT9	HT9	3 pcs	T91
11	ODS	NF616	3 pcs	T91

As shown in Figure 1, for the lap welding, the flyer piece was driven onto the target piece by a “driver”, which is made of copper. The driver is accelerated electromagnetically and hit the flyer at a speed above 300m/s. The collapse between the flyer and target piece can generate an atomic bonding and a very thin melt layer can be formed during this process.

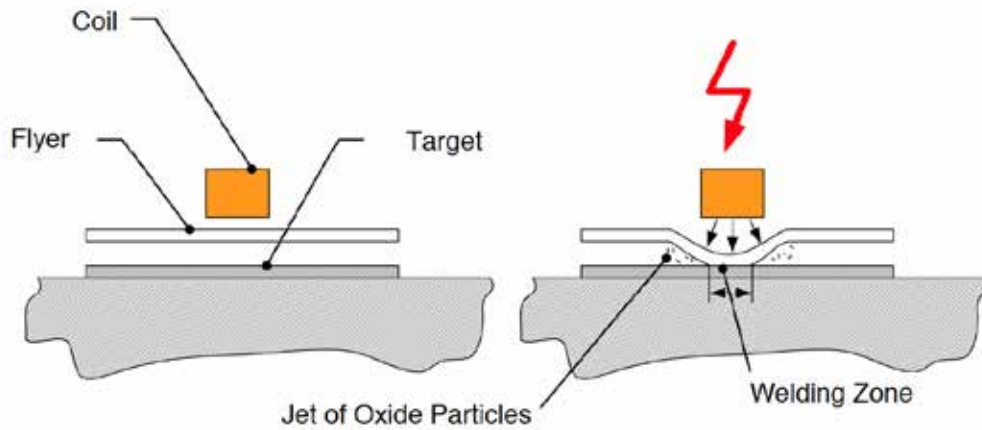


Figure 1. Schematic drawing of the lap welding using pulsed magnetic welding.

Figure 2 shows the set up of EMPT-system PS80-10, and the welding was performed using a high-performance coil with the maximum output of 120KJ. The specially designed field former was used to match the size of the cladding tube, and as shown in the picture, a copper driver (sleeve) was also used to drive the tube onto the plug. And the electromagnetic field in the former was simulated using ANSYS (FEM).

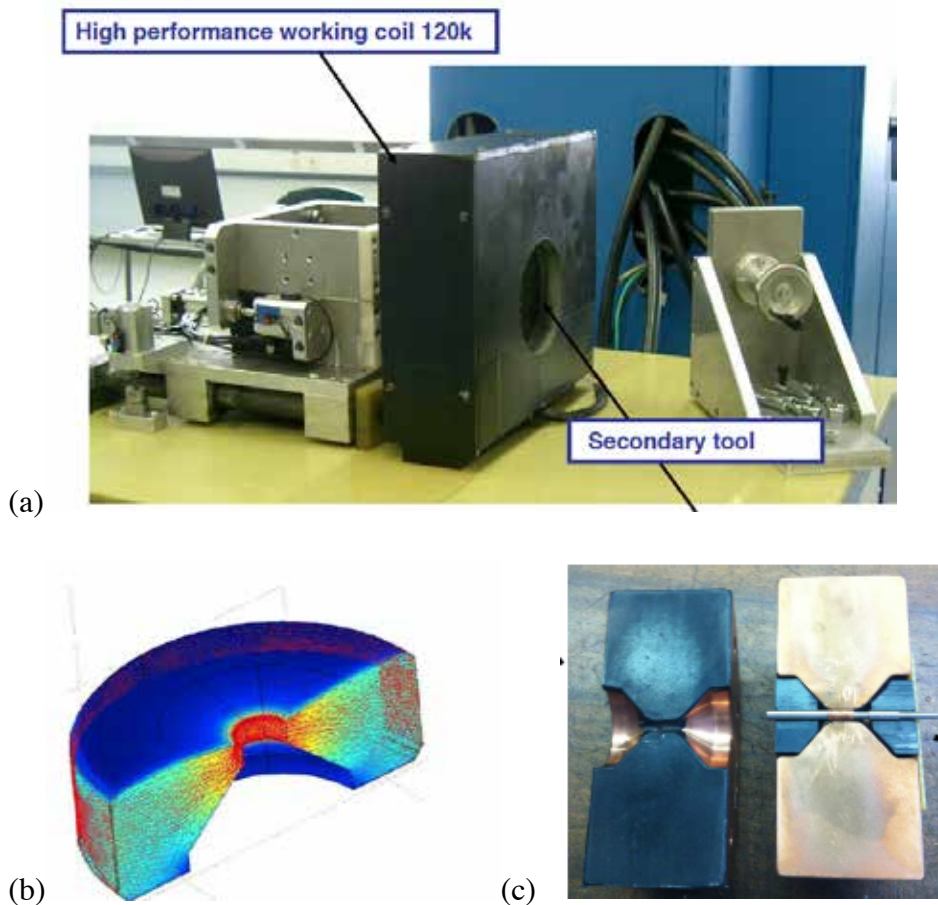


Figure 2. EMPT system (a) with specially designed field former (c) based on the FEM simulation (b).

Lap welding was tried for the different combinations as listed in table 3.2, unfortunately, the results for the F/M steels were not good, and the welding can be easily peeled off handily, as shown in figure 3, though a small amount of shining bond can be seen on the edge of the impression.

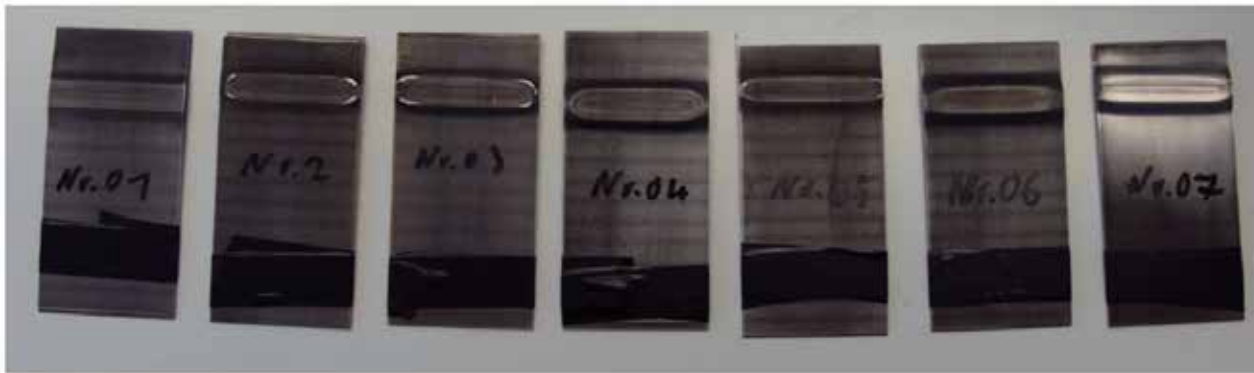


Figure 3. Lap welding couples after manually peeling test.

For the HT-UPS, the lap welding turns be very successful, as shown in figure 4, a strong bond between the pieces was achieved. The possible reason for the poor welding on F/M steel can be due to the high tensile/yield of F/M steels, and the surface finish directly from EMD machining can also be problematic since the oxides on the machined surface will prevent the formation of atomic bonding. While the welded surfaces of HT-UPS were mechanically grinded before welding, which also incurred an extremely high cost.

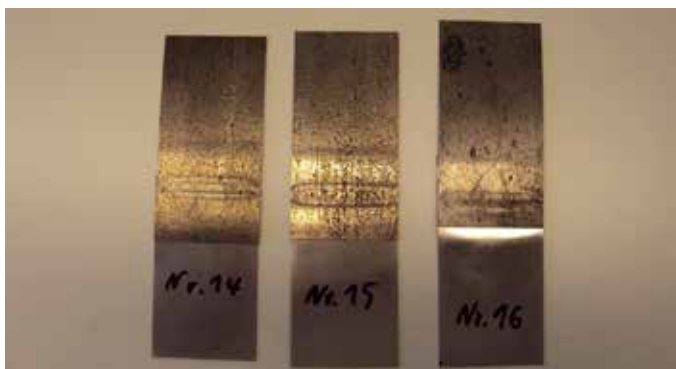
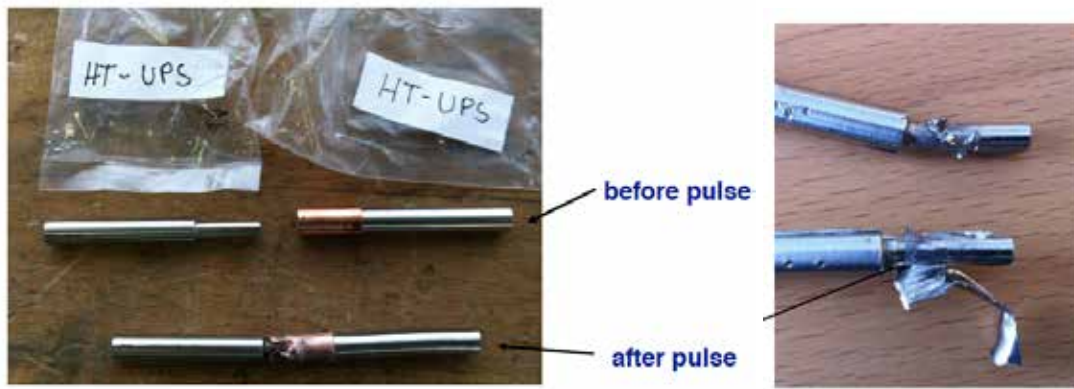
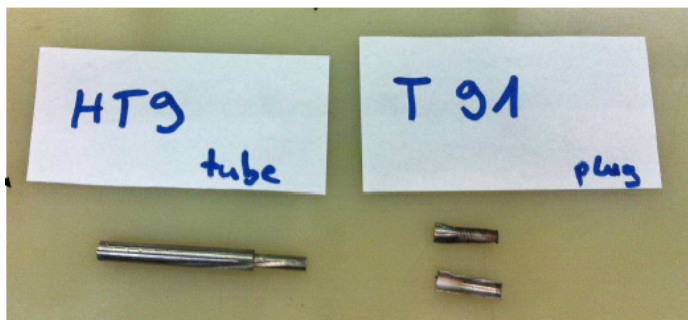


Figure 4. Lap welds of HT-UPS flat coupons.

Tube/plug welding tests were also performed based on the listed combinations in Table 3.2. HT-UPS steel shows the best weldability, while the welding on F/M steels has a minimal metallurgical bonding as shown in the peel tests of figure 5 (a)-(f).



(a) HT-UPS welds and peel test



(b) HT9/T91 welds and peel test



(c) NF616/NF616 welds and peel test



(d) ODS/NF616 welds and peel test



(e) ODS/HT-UPS welds and peel test



(f) ODS/ODS welds and peel test

Figure 5. Tube/plug welds and peel tests.

Overall, the first batch of welding tests clearly demonstrate the difficulty in welding the F/M steels, while the austenitic steel HT-UPS can be readily welded. The possible reasons are the combination of high yield strength and relatively low electrical conductivity, and the surface finish can also be a deterministic factor. The welding on HT-UPS can yield a similar strength of the matrix materials based on the tensile test. Particularly, for the tube/plug welds, the flying distance of the cladding tube onto the plug was limited by the small clearance between the tube and plug.

Welding campaign #2

As one of the optimal parameters that significantly affect the strength of weld bonding, the sample geometries of the tube and end plug were reconsidered. The angle between the moving component (the tube) and the static central end cap is very critical, and it determines the flight distance of the tube prior to collision. As shown in figure 6, two different tapped angles of 5° and 7.5° were tried. Larger angle tends to allow a higher acceleration achieved by the tube as a result of electromagnetic pulse. And the tapped angle would allow the tube to collapse onto the plug at different speed. As compared with our previous design, the diameter of the straight part of the plug is also increased from 5mm to 9.6 mm, and correspondingly, the inner diameter of the tubes is also increased to 9.6mm and OD is 10.4mm. Table 3.3 gives the list of materials combination for this round of experiments.

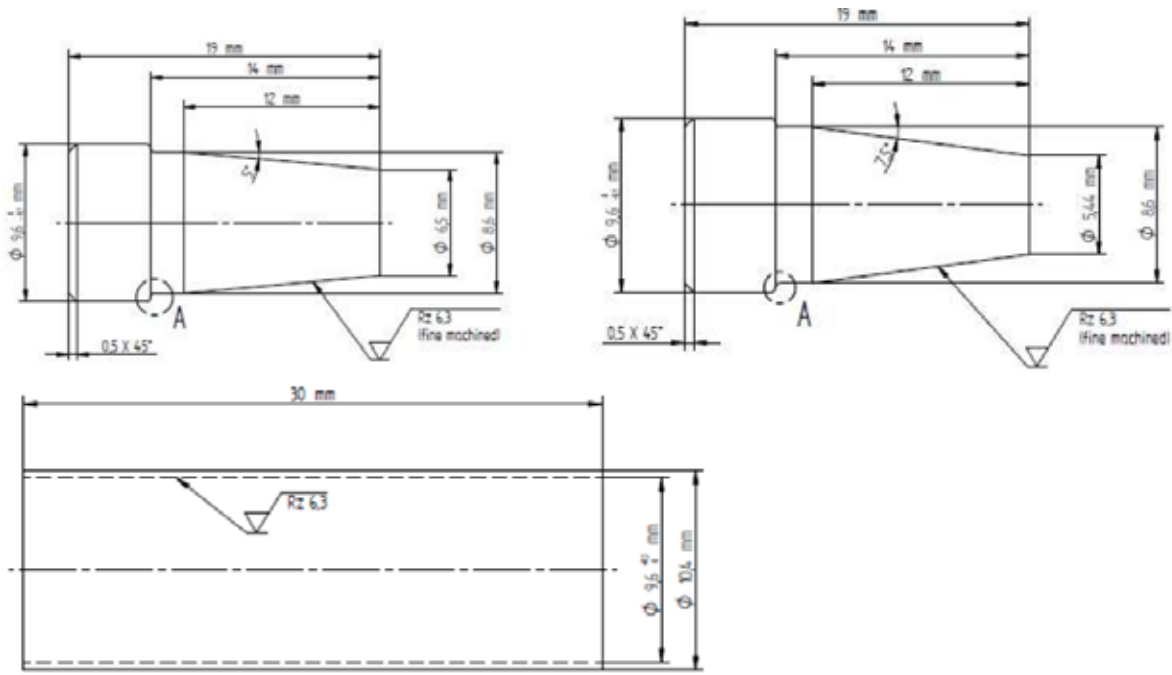


Figure 6. Two new designs of end plug with the taper angles, and the dimensions of tube.

Table 3.3. List of materials and welding matrix with optimized geometry.

Material	Welding type
NF616	Tube/plug, with 5.0° taper angle
	Tube/plug, with 7.5° taper angle
ODS	Tube/plug, with 5.0° taper angle
	Tube/plug, with 7.5° taper angle
ODS/NF616	Tube/plug, with 7.5° taper angle
NF616	Sheet welding with Cr coating
	Sheet welding with Ta coating
ODS	Sheet welding with Cr coating
	Sheet welding with Ta coating
ODS/NF616	Sheet welding with Cr coating
	Sheet welding with Ta coating

To accommodate this new design, a new set of BS5 magnet field shaper was also designed and manufactured, as shown in figure 7. The picture on the right side shows where the copper driver was mounted.



Figure 7. Newly designed and machined magnet field shaper.

FEM simulation was also performed to facilitate the welding optimization, as shown in Figure 8. The multi-physics model shows that the impact velocity is high enough to react the temperature above the melting point of steel locally, and a solid metallurgic bond should be formed between the tube and plug.

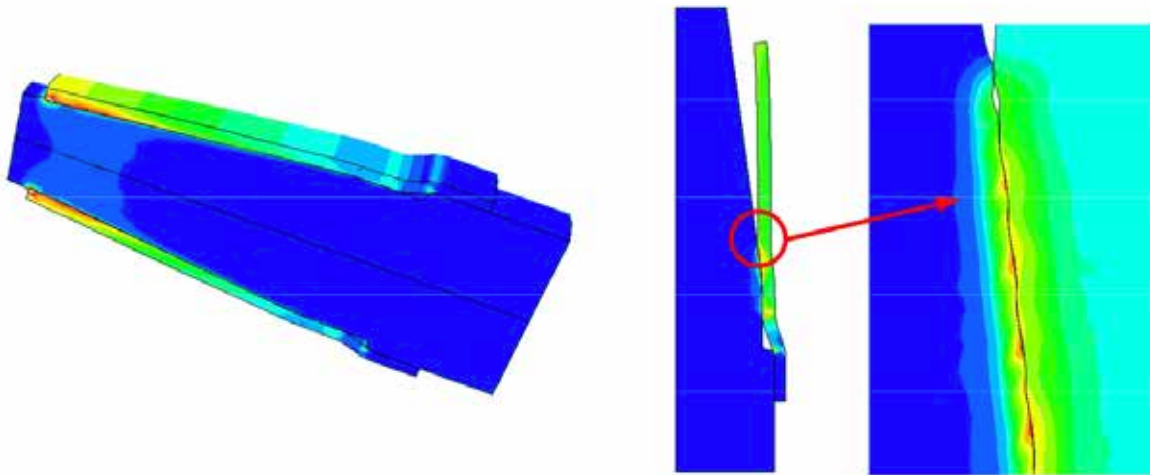


Figure 8. FEM of the welding process, showing high temperature spots locally from impact.

Welding was also trialed on the pilot stainless steel (European Grade X20Cr13), the pins have a taper angle of 5 or 7°. The copper was made from Cu58 with a length of 14mm. As shown in figure 7, the copper driver drives the tube to collapse on the pin.

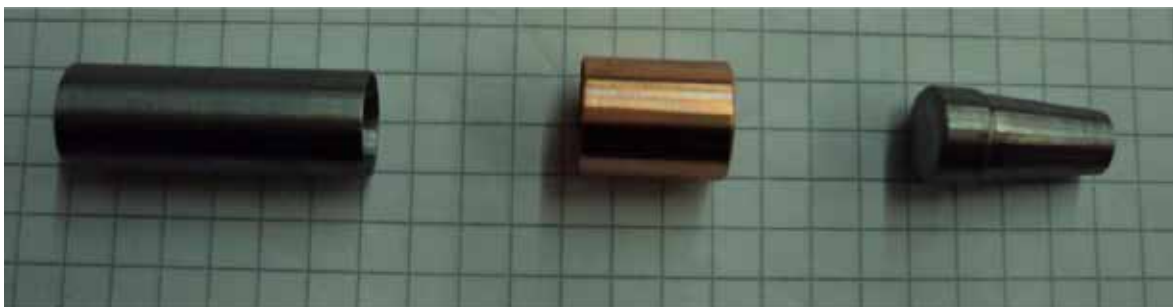


Figure 7. Tubes, plugs and copper driver for PMW tests.

Several welding tests were performed, and the mechanical peel tests were conducted on the welding tube/plug set. As shown in figure 8, the peel tests showed successful welds were achieved particular on the 7° tapered pins. Table 3.4 gives the summary of the optimized welding parameters.



Figure 8. Tube/pin weld after mechanical peel test.

Table 3.4 Optimized welding parameters for tube/plug welds.

Current	Frequency	Voltage	Energy	Pin	Results
238,6 kA	14,9 kHz	15,66 kV	25 kJ	7,5°	Satisfactory peel test results

For the flat coupon welding, as an example shown in Figure 9, one end of the flat coupon were electropolished using a solution of 10% HClO_4 balanced with methanol. All the coupons were thoroughly cleaned using acetone and methanol before the coating.



Figure 9. Examples of electro-polished and coated flat coupons.

A DC sputtering coating process was used for the coating. Both Ta and Cr were applied on different combinations of flat pairs. The coating was performed in a vacuum down to 2×10^{-6} Torr and the stainless steel substrates were maintained at room temperature. The thickness was controlled to 200 nm by using a crystal deposition thickness monitor. The equipment is shown in figure 10.



Figure 10. DC sputtering coater for depositing Ta and Cr thin films.

Unfortunately, all of the flat welded coupons were lost during the shipping to Germany, and they were un-replaceable due to the unavailability of raw materials, and it was unable to retrieve the post welding examination and test data.

Post welding characterization

Beside the mechanical peel tests selectively performed on-site immediately after welding, helium leak test, tensile test, optical and transmission electron microscopy were also performed on those weld samples.

Tensile test

Since only the HT-UPS lap welding shows a strong metallurgic bonding upon the mechanic peel test, tensile tests were only performed on those coupons. Basically, each of the flat lap weld was sliced into four tensile specimen. As shown in Figure 11, specimen #1 and #4 were cut from the edge of the flat lap weld (shown in figure 11), while specimens #2 and #3 were sliced from the center for the flat lap weld. As shown in figure 12, consistently, specimen #2 and 3 show the highest welding strength and the specimen fractured at the metal matrix, while specimen #1 and 4 fractured immediately after loading because those two specimen were partially jointed since they were sliced from the edge of the lap weld.



Figure 11. Tensile specimen of lap welds after tensile tests.

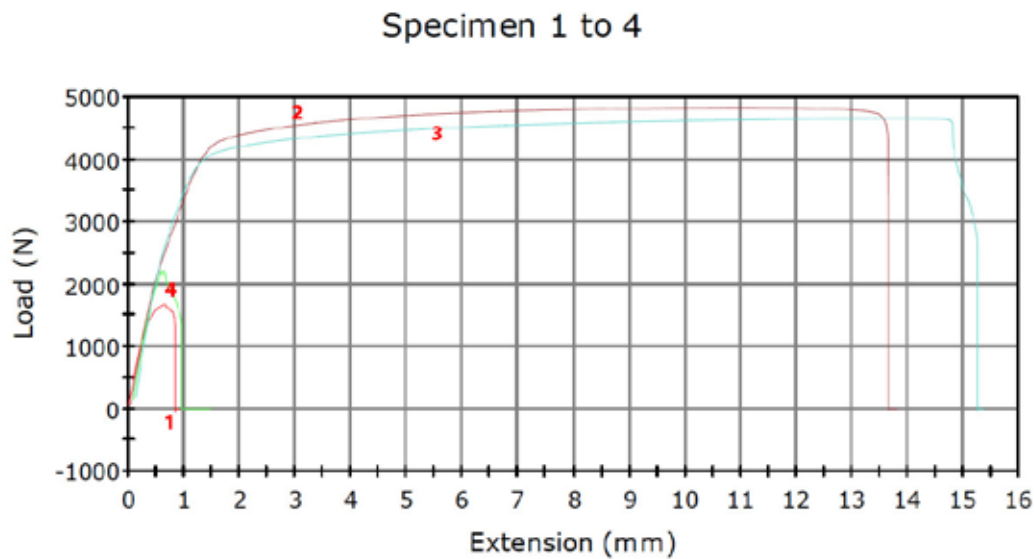


Figure 12. Curves of tensile tests on specimens #1-4.

Helium leak tests

To further quantify the integrity of welds, helium leak tests were performed on those tube/plug welds. The set up is shown in Figure 12, and after vacuuming the welds, helium was purged onto the outside of the welds using a purging cup, and the results are summarized in Table 3.5. It can be found that in general high taper angle of 7.5° tends to have a better welding quality than those of low taper angle of 5° . Among those combination of materials, welds between NF616 and NF616 gives the best welding quality.



Figure 13. Set up for helium leak tests.

Table 3.5: Summary of helium leak tests on the tube/plug welds.

Materials (tube/plug)	Taper angle (°)	Vacuum (mbar/s)	Leak rate (mbar/s)	Note
NF616/NF616	5	5×10^{-9}	4.1×10^{-6}	Significant leak
		5×10^{-9}	5×10^{-8}	Slight leak
		4×10^{-9}	3×10^{-6}	Significant leak
		5×10^{-9}	2.3×10^{-5}	Significant leak
	7.5	3×10^{-9}	3×10^{-9}	No leak
		8.6×10^{-10}	8.6×10^{-10}	No leak
		9.5×10^{-10}	9.5×10^{-10}	No leak
		1.3×10^{-9}	1.3×10^{-9}	No leak
T91/T91	7.5	5×10^{-9}	3.7×10^{-9}	No leak
T91/ODS	5	2×10^{-8}	2×10^{-3}	Significant leak
		2×10^{-8}	2×10^{-4}	Significant leak
T91/ODS	7.5	5×10^{-9}	5×10^{-9}	No leak
		8×10^{-9}	1.3×10^{-4}	Significant leak

Optical microscopy imaging

Cross section samples in two directions were prepared by using a standard metallurgical processing, and the representative optical images are shown in Figure 14. It can be seen that the gap starts to close up towards to the end of the tube, and it becomes invisible eventually. The etched sample on the right shows the welding line clearly.



Figure 14. Cross-sectional samples in tube axis and radial directions, respectively.

Transmission electron microscopy

The TEM specimens at the welding line were prepared using FIB, and the TEM studies were performed using a JEOL ARM200 at FSU. Clearly, the welding shows a solid metallurgic bond as in Figure 15, and the welding line might consist of a dendrite structure from very local melting. However, the TEM diffraction wasn't able to find whether it is a non-bct structure. The width of the welding line is in the neighborhood of 5 μ m, which is significantly smaller as compared with the welding zone from other welding technologies, such as, TIG, laser or e-beam welding.

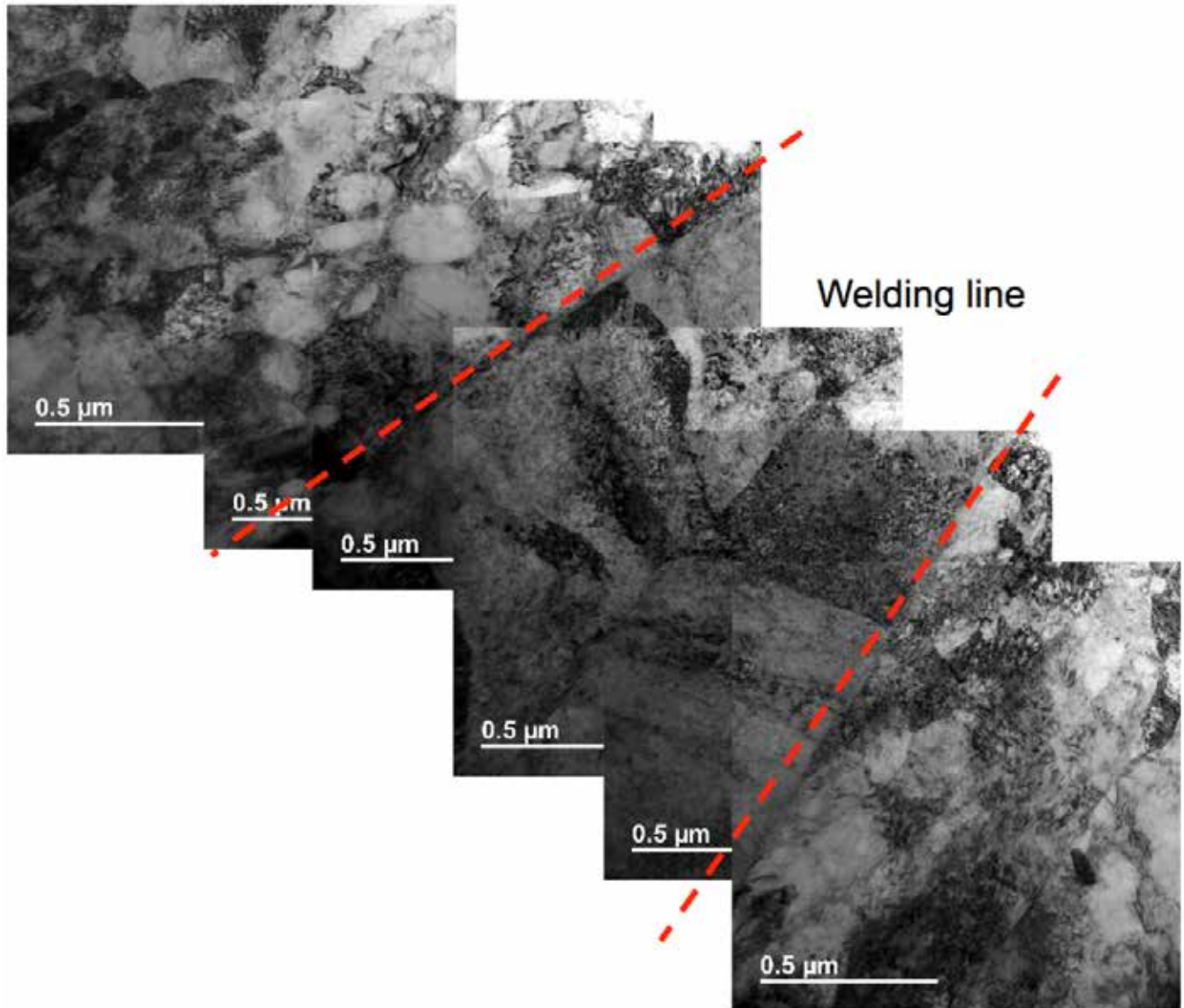


Figure 15. TEM image of the welding line in NF616 tube/plug welds.

Irradiation stability

As discussed in the section of background, one of the concerns for the fusion welding technology is that the nuggets from welding might have a compromised response to the irradiation from their base metals. For this study, both the as-received and welded specimens were irradiated using a 5 MeV Ni²⁺ ions at

400°C, and the dose was up to 50dpa. The irradiated microstructure of HT-UPS was characterized using TEM on the FIB specimen, while the studies on the oxide precipitates of ODS were performed using APT. In general, there is no dateable difference between the as-received and welded specimen regarding to the radiation response. Figure 16 (a) shows the TEM image of in the welded zone, and Figure 16 (b) shows the irradiated microstructures. The irradiation induced a high density of dislocation loops while no voids were identified.

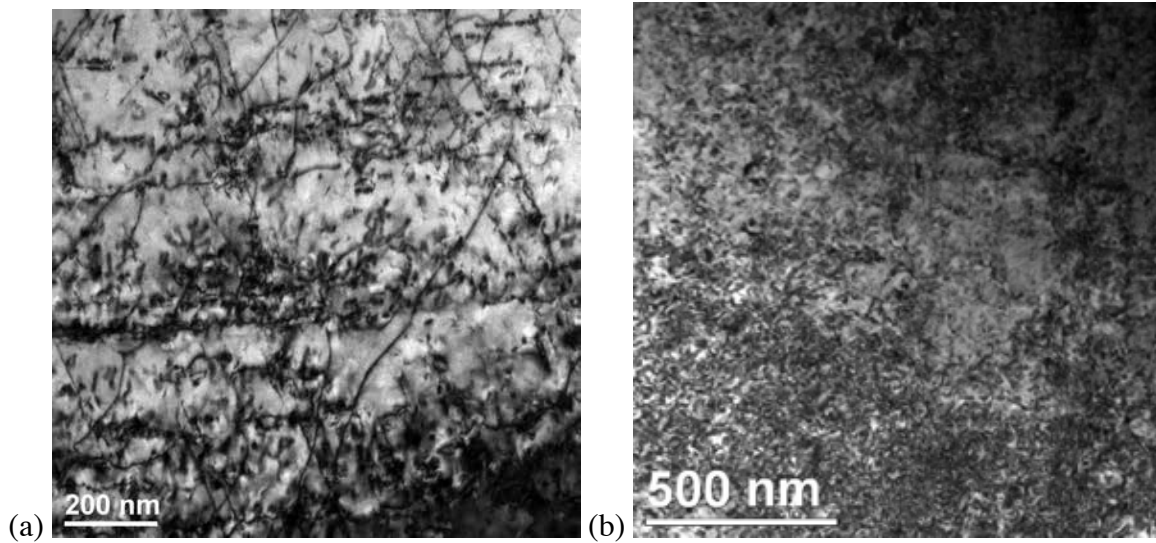
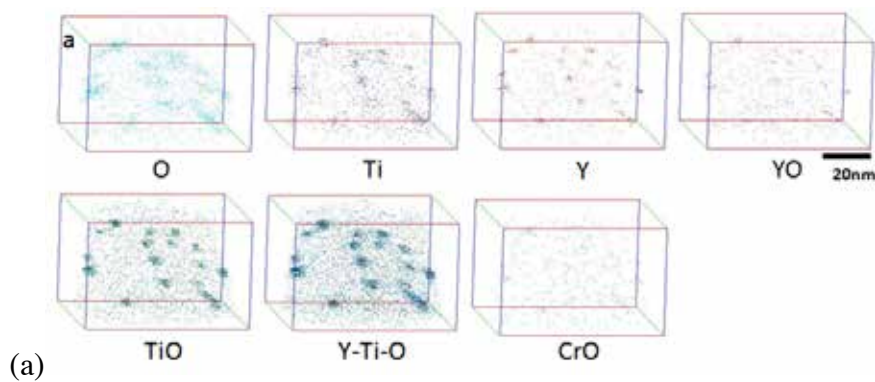


Figure 16. TEM images of welded HT-UPS: (a) as welded and (b) irradiated to 50 dpa.

The APT results in Figure 17 of the irradiated ODS steels also shows that the irradiation does induce coarsening of the nano precipitates. Nevertheless, the welds demonstrate a very similar irradiation response as compared with its base metals.



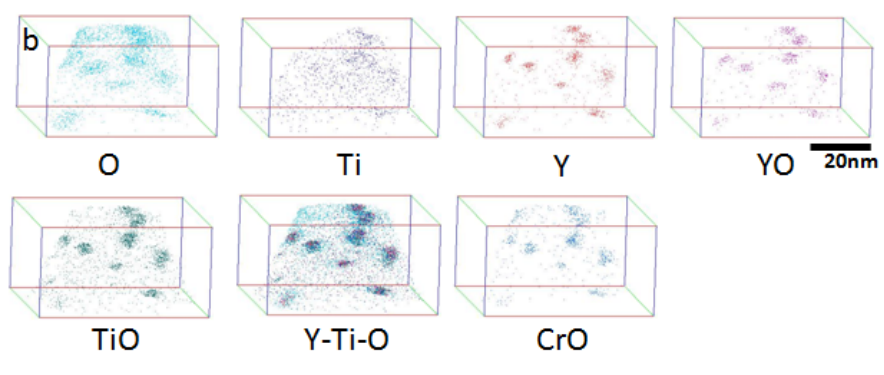


Figure 17. APT results of ODS welds: (a) un-irradiated and (b) irradiated.

Reference

- [1] W. F. Brown, J. Bandas and N. T. Olson, Welding Journals, June (1978), p.22
- [2] R. L. Klueh, “Joining and Processing issues for Ferritic/Martensitic Steels”, presented at US Fusion Materials Science Program Strategic Planning Meeting, University of California at Santa Barbara, August 26-30, 2002.
- [3] “Fabrication Technology for ODS Alloy MA957”, PNL-13165, Feb. 2000
- [4] D. S. Bae, S. K. Kim, S. P. Lee, H. Kinoshita, T. Shibayama and H. Takahashi, Fusion Science and Design 81 (2006), p.969
- [5] S. Kaga, T. Tamura, H. Yoshida and K. Miyata, J. Nucl. Mater. 179-181 (1991), p.588
- [6] T. S. Morgan, E. A. Little and R. G. Faulkner, 16th Radiation (1994), p.607

Publications:

Y. Yang, Sindo Kou and Todd Allen, Pulsed Magnetic Welding for Advanced Core and Cladding Steels, TMS 2012.

Yong Yang, Todd Allen and Sindo Kou, Characterization on the Advanced Core and Cladding Steels after Electro Magnetic Pulse Welding, TMS 2013

Wei-yang Lo and Y. Yang, “Pulsed Magnetic Welding on NF616 and its response to ion irradiation”, manuscript prepared for the Journal of Nuclear Materials.