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ELECTROMAGNETIC PULSE TECHNOLOGY AS A MEANS OF JOINING GENERATION IV CLADDING MATERIALS

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ABSTRACT

The Institute for Transuranium Elements (ITU) has conducted investigations into the possibility of using Electromagnetic Pulse Technology (EMPT) in joining PM 2000 ODS and T91 ferritic-martensitic steels, using samples fabricated to simulate tube and end caps. The investigations are primarily directed towards the joining of cladding tubes to enable fuel pins to be produced in its laboratories. A suitable field former was fabricated and the tests coordinated and financed by ITU were carried out initially by a specialist EMPT company.

To date, joints with a helium leak rate of leak in the range 10^{-8} mBar.litres.s⁻¹ have been achieved. Further refinement of the parameters is now being done in order to improve the weld quality and achieve the target leak-rate of 1.0×10^{-9} mBar.litres.s⁻¹

Keywords:

Generation 4, T 91, ODS, electromagnetic pulse.

INTRODUCTION

The need for a reliable method for joining T91 and ODS steels is central to the fabrication of fuel pins using these materials. Post-joining heat treatment of a fuel pin cladding that does not have detrimental effects on the fuel is practically impossible in a nuclear facility. Whereas other reactor components made from these materials may be discarded due to defective joints, fuel pins must be reopened and the contents recuperated. Thus the application of any joining technology to fuel pin fabrication demands reliability and simplicity of operation.

Electromagnetic Pulse Technology (EMPT) has come into consideration for this purpose for several reasons:

- It is a technology with proven repeatability, with widespread applications in mass-production processes.
- The solid state joint produced does not adversely affect either the heat treatment of T91 or the particle-dispersion consistency of ODS steel. Problems associated with a heat-affected zone, like grain growth, are eliminated.

EMPT has been used in the past for the fabrication of fuel pins with conventional cladding, but is not widely used in the nuclear industry. More recently, ODS has been successfully joined by this method [1]. The primary objective of the tests described in this work is to define the parameter limits that are effective for repeatable, acceptable joining of T91-T91, and ODS-ODS fuel pin components, with a geometry suited to that purpose. Within these limits, more extensive investigations involving material characterization will be carried out and reported separately.

NOMENCLATURE

EMPT: Electromagnetic Pulse Technology uses the stored energy from a charged capacitor bank to deliver a current to a coil. The resulting eddy currents between the coil and the field former produce an explosive force that can be used to deform or join components.

GESA: The acronym GESA is derived from "Gepulste Elektronenstrahlanlage" (Pulsed Electron Beam Facility). It is a treatment that causes a surface modification of steels to increase their corrosion resistance.

EUROTRANS-DEMETERA: DEMETERA is the acronym for the Domain 4 of the EUROTRANS integrated transmutation

project. It derives from DEvelopment and assessment of structural materials and heavy liquid MEtal technology for TRansmutation systems.

GETMAT: This is a Framework 7 Programme project which is derived from GEn IV and TRansmutation MAterials.

ODS: Oxide dispersion strengthened steel is a candidate material for Generation IV cladding materials, due to its creep resistance at high temperature.

T91: This is another Generation IV candidate material for fuel pin cladding and reactor components. It is a ferritic-martensitic steel which derives its strength and creep resistance from heat treatment.

2. Experimental

2.1 Materials used

The materials used in this study were (a) T91 reference material supplied by EUROTRANS-DEMETERA project partners and (b) PM 2000, from Plansee Metals. The compositions of these materials are given in Table 1:

Table 1: Compositions of the materials used

	T91	ODS
	Composition %	
C	0,1	0,014
Cr	8,99	13,87
Ti	0,0034	1,05
Mo	0,89	0,3
Mn	0,38	0,1
Ni	0,11	-
Si	0,22	0,04
Al	0,01	0,1
S	0,0004	0,006
P	0,021	0,004
V	0,21	
Nb	0,06	
Cu	0,06	
Y		0,22
Fe	Balance	Balance

Yttrium is present in ODS in the form of dispersed oxide particles, which tend to agglomerate when the material melts, leading to diminution of their strengthening properties at the joint. This has serious consequences for Tungsten Inert Gas, Electron Beam welding and other methods where melting of the parent metal leads to unfavourable redistribution of the oxide particles. With T91, the heat treatment from which the material derives its strength and creep resistance is adversely affected by conventional welding processes.

2.2 Test conditions and equipment

The T91 samples were tested in their as-received condition, that is, without heat treatment. They were cut from plate material by pressurized water-jet to avoid thermal influences and machined to the required geometry.

The surface roughness (Rz) of 6.5µm corresponds to fine machined surface finish. Rz of 1.5µm is achieved by polishing with grit size 2000. All tests were conducted in air. Samples were degreased with Acetone prior to testing. The devices used for the tests were (a) a 60 kJ capacity Electromagnetic Pulse unit, used for preliminary tests in collaboration with a supplier of EMPT equipment [2], and (b) a 100 kJ unit, purchased by ITU (Figures 1 and 2), with a custom-built field former for the sample geometries described here. The split field former is seen in the foreground in the open position, with its coil socket in the background on the same axis.



Figure 1: 100 kJ EMPT device installed at ITU

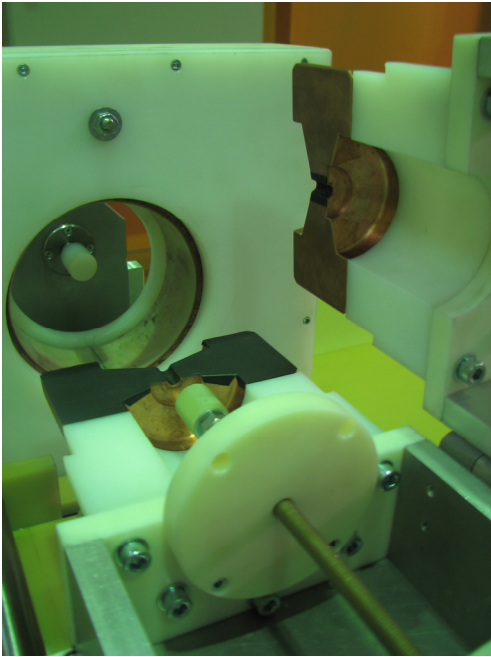


Figure 2: The field former of ITU's EMPT device

2.3 Parameters

The investigation of optimal parameters must take account of all factors that can contribute to the result. The factors foreseen initially were sample geometry and energy input. The surface roughness of the colliding surfaces was only considered after preliminary tests.

The sample geometry is recognized as one of the critical factors. The sample consists of the cladding tube and an end cap of a specific design, which is entered in the tube. In particular, the angle of collision between the moving component (the tube) and the static central end cap is considered carefully. This angle has a strong influence on the interaction between the components during the deformation but it also determines the flight distance of the tube prior to collision. This distance is critical in allowing an optimization of the acceleration achieved by the tube component as a result of the electromagnetic pulse. In effect, it enables a range of velocities at impact along the interface of the components. The starting design was chosen to maximize the reusability of the relatively scarce material resources. Successive iterations, based on successive test results, were characterized by progressive increases of the included angle and shortening of the conical section from the original 25mm to 10mm and then 9mm, (see Figures 3, 5 and 8).

The tube geometry remained constant throughout the tests. The outside and inside diameters (8.5 and 7.5 mm respectively) were defined in agreement with GETMAT project partners, to simplify the ongoing comparison of results.

3. Results and discussion

3.1 First tests

As a result of preliminary tests, the initial end cap geometry, shown in Figure 3, was recognized as unsuitable for joining the materials. The design used was an approximation taken from a report [2] on an early fuel pin fabrication technique using EMPT in the 1960s, Maxwell Magneform [3] equipment and various cladding materials (316 Stainless steel, Inconel 706, PE 16 and RA 330). The samples were crimped to a common geometry but no evidence was found of even localized joining (see Figure 4). This was confirmed by helium leak tests, which gave values of an unacceptably high leakage, (see Table 2).

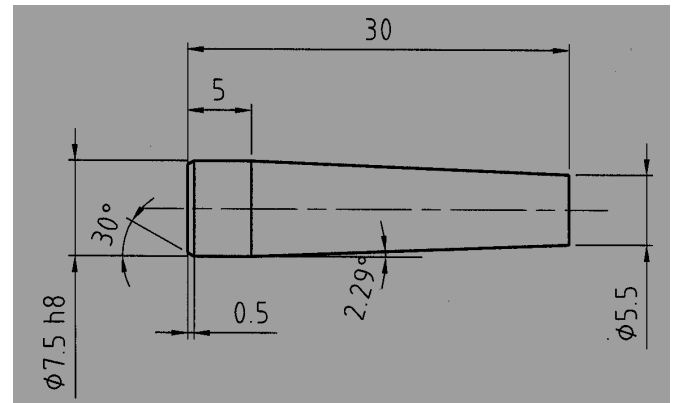


Figure 3: Starting end cap geometry, T91.

Table2: He-leak rate of geometry 1 end caps, T91.

No.	Leak Rate (mbar.l.s ⁻¹)	Pulse Energy (kJ)
1	5,0 x 10 ⁻⁵	40
2	5,0 x 10 ⁻⁵	40
3	5,0 x 10 ⁻⁵	40
4	5,0 x 10 ⁻⁵	40
5	5,0 x 10 ⁻⁵	40

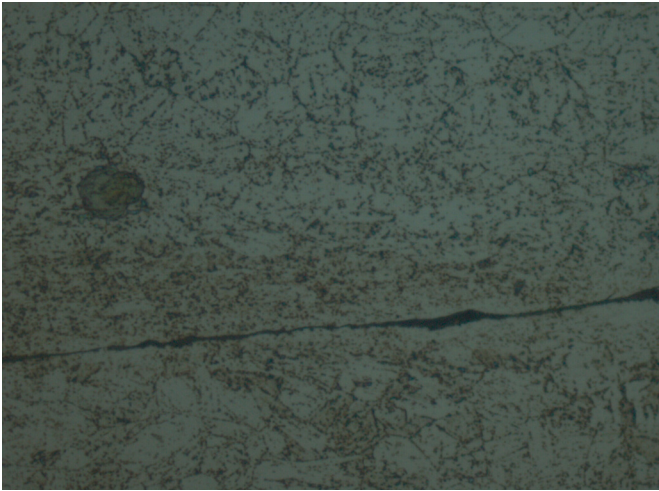


Figure 4: Optical microscopy of geometry 1 joint at its minimum width, T91.

The failure to achieve joining with this initial configuration was not unexpected. The geometry was based on the necessities of more conventional, more ductile materials. The geometry allowed unused samples to be re-machined to a new, shorter conical form for further tests (see Figure 5). However, it was obvious that the close contact, as shown in Figure 4, achieved by crimping could be utilised as part of a later “hybrid” joining solution, where mechanical strength could be gained by this means, allied to leak-tightness possibly at a zone with inferior strength.

3.2 Re-design

Figure 5 shows the design used for the second series of tests. With the increase in energy applied from 40 kJ to 50 kJ, it became apparent that a different driver material was needed, as the AlMg₃ T4 was destroyed during welding. The copper alloy E-Cu 57 (2.0060 DIN 1708) was used as a higher-strength replacement. With the introduction of a step-down in diameter from 7.5 mm to 6.5 mm it was hoped to achieve a “whiplash” effect, i.e. with increased acceleration.

The leak rates of the samples produced using this design are given in Table 3. A dramatic improvement in leak rate is found, but it is still not sufficient to meet fuel pin applications. Metallographic examination (Figures 6 and 7) show that partial joints have been made, but they are by no means complete. This necessitated further design and optimization of geometries. The results here gave reasonable grounds for confirmation that the process could effectively join T91 cladding material of this geometry. It was clear that helium could leak through the non-joined zones but both the measured leak-rates and the optical examinations suggested that the non-joined zones were limited in extent.

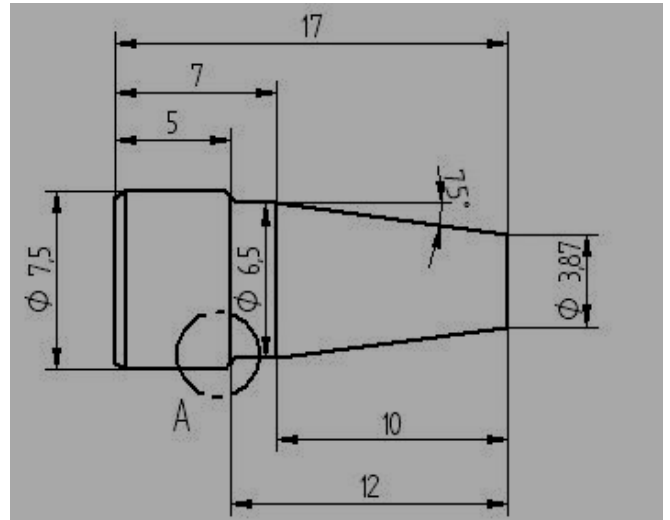


Figure 5: Derived end cap geometry 2, T91

Table 3: He-leak rate of geometry 2 end caps, T91.

No.	Leak Rate (mbar.l.s ⁻¹)	Pulse Energy (kJ)	Surface Roughness (Rz) μm
1	4,7 x 10 ⁻⁷	50	6,5
2	5,5 x 10 ⁻⁷	50	6,5
3	1,8 x 10 ⁻⁶	50	6,5
4	3,1 x 10 ⁻⁷	50	6,5
5	4,4 x 10 ⁻⁷	50	6,5



Figure 6: Optical microscopy of a joint segment with end cap geometry 2, T91.

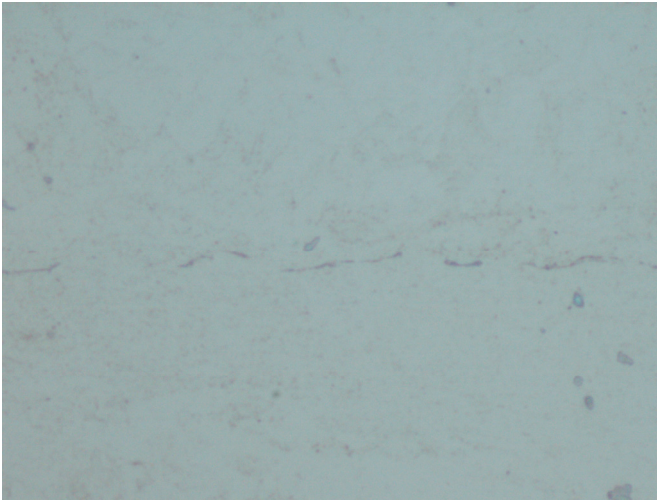


Figure 7: Optical microscopy of a joint segment with end cap geometry 2, T91, at a magnification of 500x.

3.3 Third design geometry

Because of the strong evidence of improvement in the previous design, it was decided to proceed in the same way, namely shortening the cone length thereby increasing the angle of collision.

The step-down in diameter was maintained, the cone-length shortened by 1 mm and the colliding surfaces were polished to a finer surface finish (see Figure 8). This latter measure was taken to limit the passage of Helium through the joint due to the “serrated” surface profile left by machining processes. The energy input was maintained at the previous level to assess the geometry modification in isolation.

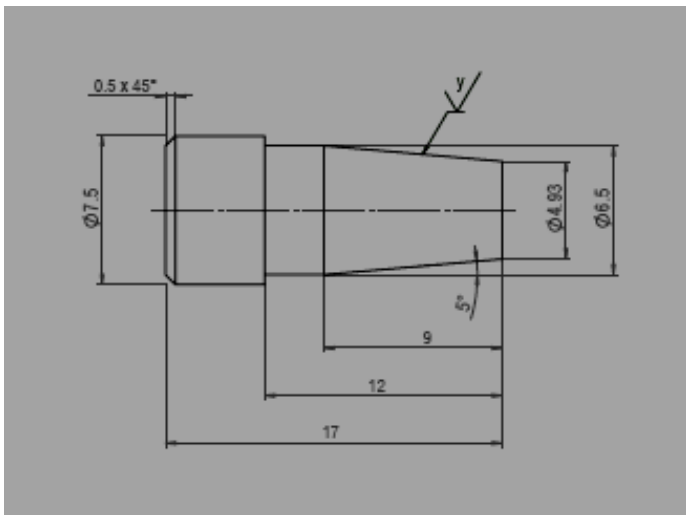


Figure 8: Derived end cap geometry 3, T91.

A substantial improvement was achieved in the leak tightness (see Table 4). Further tests will be done to verify that the improvement was exclusively through the geometry change or to quantify the influence of surface roughness. Several samples meet fuel pin specifications, but the repeatability still needs further improvement. Potentially important parameters like geometry and surface roughness have been identified and can be investigated more precisely around the conditions defined here. A reliable driver material has been identified in E-Cu 57.

Table 4: He-leak rate of geometry 3 end caps, T91.

No.	Leak Rate (mbar.l.s ⁻¹)	Pulse Energy (kJ)	Surface Roughness (Rz)
1	$3,0 \times 10^{-9}$	51	1,5
2	$1,0 \times 10^{-9}$	51	1,5
3	$1,8 \times 10^{-9}$	51	1,5
4	$7,0 \times 10^{-9}$	51	1,5
5	$6,1 \times 10^{-9}$	51	1,5

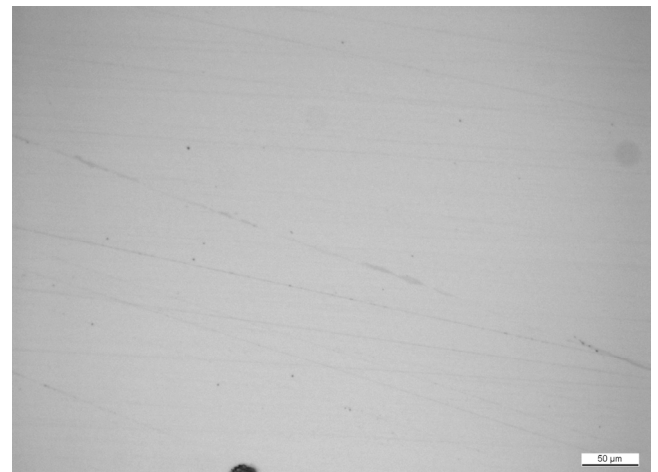


Figure 9: Optical microscopy of geometry 3 joint at its minimum width, T91.

3.4 Tests with ODS

With the progress to date on T 91, it was decided to apply the derived conditions to samples of ODS using geometry 3 (both components were ODS, the tube form being machined from solid due to the non-availability of manufactured tube). While it was considered unlikely that the same parameters could be valid for two materials with different compositions and strengthening mechanisms, the comparison in results could be considered valuable. More energy (62 kJ) was needed as pre-tests yielded inferior joining results.

Although limited in scope, the tests to date with ODS have shown that the optimized conditions are unlikely to be

substantially different from those of T 91, especially as similar helium leak rates were achieved (see Table 5).

Figure 10 shows the area (at the centre of the image) where the termination of the non-joined interface of the components occurs.

The energy input was greater for the same result. The reserve capacity available with the recently purchased device at ITU should ensure that all requirements for the foreseeable future can be met.

Table 5: He-leak rate of geometry 3 end caps ODS.

No.	Leak Rate (mbar.l.s ⁻¹)	Pulse Energy (kJ)	Surface Roughness (Rz)
1	7,0 x 10 ⁻⁹	62	1,5
2	1,1 x 10 ⁻⁸	62	1,5

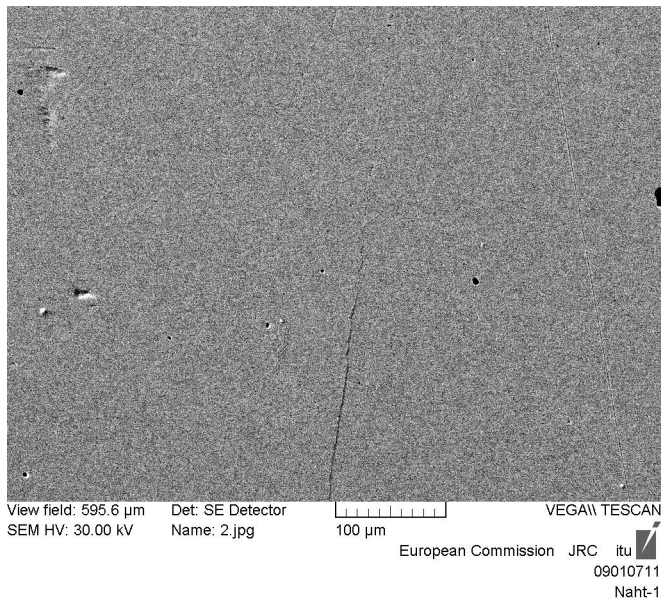


Figure 10: SEM image of joint showing the transition zone from non-joined (line from bottom) to joined (ODS).

4. Conclusions

The objective of defining a parameter window for the joining of advanced cladding materials (T91 and ODS steel) for Gen IV reactors has been achieved. A sample with optimized geometry is shown in Figure 11. Future tests will be performed to close in on the optimum conditions. Due attention can be given to a more precise angle of collision and surface roughness, as well as the investigation of the effects of the process on the material's microstructure and properties.



Figure 11: Welded sample with geometry 3

There are many advantages associated with EMPT for fuel pin fabrication with the materials described here. It can potentially make joining of these materials simple, reliable and repeatable. It involves no physical contact with the cladding at the joint, which could even enable the joining of cladding materials with dedicated coatings, e.g. GESA [4], needed for aggressive liquid Pb reactor coolants. Testing EMPT on such coated cladding is one of the priorities of the next stage of investigation.

There are some disadvantages. The financial cost of the equipment is substantial. Not all materials and geometries are suitable for this process. If a driver is necessary, it consumes energy in being itself deformed as part of the process. Finally, despite the lack of physical contact with the components, it has been observed during these tests that damage occurs at the interface between the two halves of the field former, due to the reaction forces.

It is foreseen that when optimization of the parameters has been completed, the investigations will be widened in scope to examine microstructure effects in the cladding, burst strength at high temperature, effects on coated cladding and irradiation studies of EMPT joints. In addition, the GETMAT project foresees investigations with long-term exposure of EMPT-joined samples to molten lead coolant.

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