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FIRST RESULTS OF LASER WELDING OF NEUTRON IRRADIATED STAINLESS STEEL

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First results of experimental investigations on the laser reweldability of neutron irradiated material are reported. These experiments include the manufacture of 'heterogeneous' joints, which means joining of irradiated stainless steel of type AISI 316L-SPH to 'fresh' unirradiated material. The newly developed laser welding facility in the ECN Hot Cell Laboratory and experimental procedures are described. Visual inspections of welded joints are reported as well as results of electron microscopy and preliminary metallographic examinations.

1. INTRODUCTION

In an experimental fusion reactor like NET or ITER the replacement of nuclear components during the machine operational life is integrated in the design [1]. Potentially critical areas are for example field joints of the vacuum vessel and coolant tubes of in-vessel components such as blankets, limiters and divertor plates. It might be unavoidable for such replacements to cut and re-join structural parts which have received a significant neutron dose. In particular the amount of helium accumulated in the material increases the possibility of weld cracking [2-6]. The heat input during welding induces helium bubble formation and bubble growth. The amount of accumulated helium due to (n,α) reactions in austenitic stainless steel of type 316L at the end of the ITER physics phase of operations will be in the range of 0.5 to 5 appm.

The effects of neutron-damage and helium accumulation on the reweldability of stainless steels are evaluated, using available irradiated material. In particular the characteristics of joints of irradiated stainless steel type AISI 316L-SPH with the same material in non-irradiated condition are investigated. Emphasis is given on the helium embrittlement phenomenon, caused by the elevated temperature tensile stresses from the heat input of the joining technique.

Laser welding has the advantage of low heat-input and is a potential technique for remote handling operations [1,7]. Therefore laser welding equipment has been designed and constructed in the Hot Cell Laboratory. Specimens are manufactured in the ECN Hot Cell Laboratory from previously irradiated material. Microstructural analysis of the welded joints is performed by scanning electron microscopy (SEM) and metallography.

2. EXPERIMENTAL

2.1. Laser welding facility in Hot Cell Laboratory

For the present work a pulsed Nd:YAG laser, LASAG type KLS311/321, has been acquired. The maximum time-average power is 260 W and the maximum peak power is 6-10 kW. The laser head has been completely modified in-house for improved parameter control and beam alignment as well as for multi-purpose use. The laser head had to be further

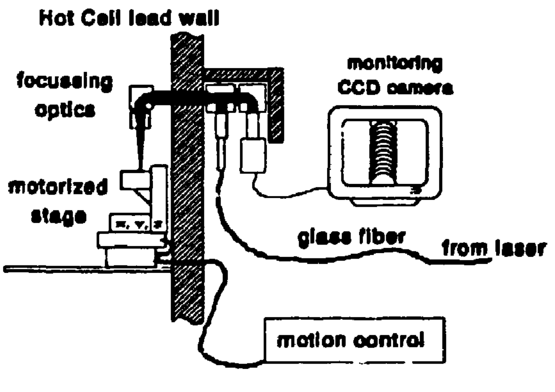

Figure 1. Schematic of set up for laser welding in hot cell.

Table 1.
Composition 316L-SPH ERHII (weight percent)

C	Si	Mn	P	S	Cr	Ni	Mo	N	Cu	Co	Ta	B	Ti	Nb	Fe
0.020	0.35	1.75	0.019	0.001	17.15	12.19	2.38	0.077	0.09	0.079	<0.001	0.0011			bal.

adjusted in order to enable the use of fibre optics from a different supplier (HAAS). The fibre has 15 m length and a core diameter of 600 μm. The HAASfibre optics was chosen for its modular composition which enables to separate fibre outcoupling optics and the focusing lens to a distance of more than 300 mm, sufficient for penetration through the 7" lead wall of the hot cell. In this way the amount of optics that needs shielding from γ-radiation is minimised. In the current set up only a deflection mirror, the 100 mm focusing lens and a protecting window are inside the hot cell. A CCD camera is connected for specimen alignment and visual inspection of the weld.

The positioning equipment which has been installed inside the hot cell allows for welding flat specimens, but modifications for a rotating table to include the possibility for welding of cylindrical specimens are planned. A clamping device was constructed in order to enable welding on both sides of the specimens, without the need for repositioning.

A schematic overview of the in-cell welding set up is given in figure 1, a picture of the hot cell interior is presented in figure 2.

2.2. Specimens

Materials in various shapes, irradiated previously in NET- and other programmes, are available with He-concentrations in a range from ppb's to more than 100 appm and damage levels of several 0.1 to 10 dpa and with irradiation temperatures in the range 50-450°C.

The welding experiments reported were performed on flat specimens, cut from Compact Tension (CT) specimens of AISI type 316L-SPH stainless steel, from the second European Reference Heat (ERHII). This material has a nominal composition as given in Table 1 [8]. It was irradiated at 80°C in the High Flux Reactor (HFR) in Petten up to 0.6 dpa. The calculated helium concentration is 7±2 appm [9].

Actual specimen dimensions for welding are 12x6 mm^2, with thicknesses ranging from 0.5 to 1.5 mm.

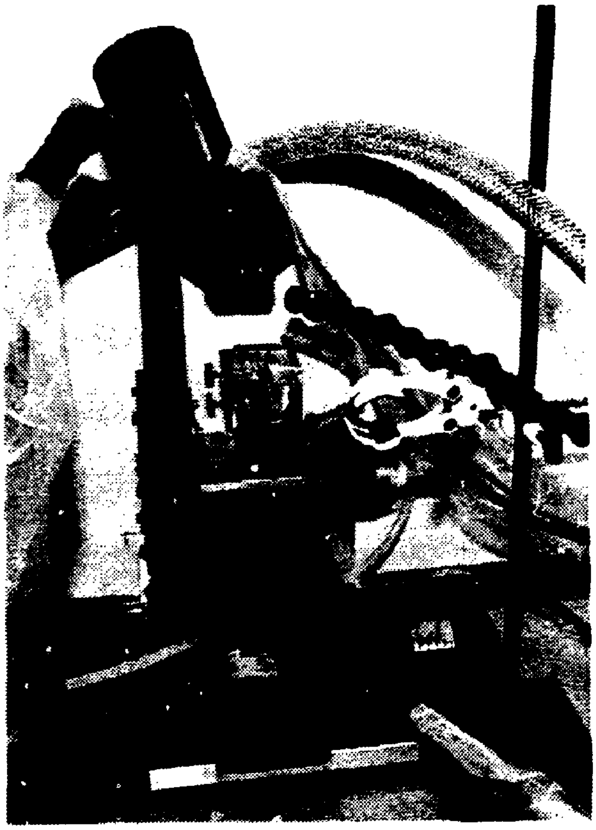

Figure 2. The interior of the hot cell for laser welding experiments.

2.3. Welding Parameters

The specimens were joined by consecutive double-sided butt-joint weld. The laser pulse duration was 6 to 8 ms and the incident pulse energy was about 7 to 9 J. Pulse repetition rate was 10 Hz, while welding speed was 180 mm/min. The weld spots had a diameter slightly larger than 1 mm. Shielding gas was argon.

3. RESULTS

3.1. Welding process monitoring

A few weldings showed spattering, which usually results in poor weld quality due to excessive oxidation. It is often caused by dirt or a too large gap. Most weldings however were spatter-free and of good appearance.

3.2. Surface inspection by SEM

For all spatter-free welds, no surface cracks (in fusion zone and HAZ) were found, this is true for unirradiated to unirradiated, irradiated to unirradiated and irradiated to irradiated welds. An example of a typical spatter-free, good appearance weld is presented in figure 3, showing a joint of unirradiated to irradiated material.

Figure 3. Micrograph of good appearance pulsed laser weld, unirradiated (top) to irradiated (bottom).

The few poorer quality welds (the ones with spattering) showed oxidation and also surface cracks in the weld pool, often together with full penetration depth. An example of poor weld quality due to excessive gap is presented in figure 4, showing a crack in the centre of the fusion zone. This crack is presented in more detail in figure 5.

3.3. Metallographic examinations

Preliminary metallographic sections showed some weld cracking and porosities, mainly in the fusion zone. The cracks appeared to be present more often in the second pass-side of the weld, they were also found in some of the welded specimens that did not show surface cracking. Final conclusions however could not yet be drawn from these metallographic results.

Figure 4. Micrograph of poor quality laser weld, irradiated (top) to unirradiated (bottom).

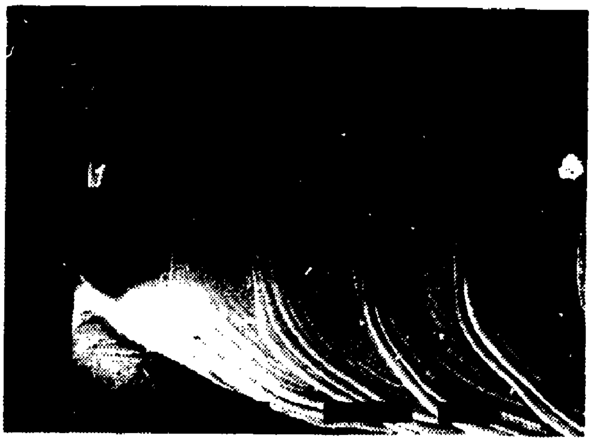

Figure 5. Detail of figure 4, showing surface crack in the centre of the fusion zone.

4. DISCUSSION AND CONCLUSIONS

The cutting of samples from existing irradiated CT-specimens has permitted a fast start of experimental work. The use of previously irradiated material also allows to study various materials with a wide variety of neutron fluences and irradiation temperatures.

Some surface cracks have been observed in welds of irradiated - but also of unirradiated specimens. This means that these surface cracks are not caused by helium effects but more likely by the sometimes poor specimen machining quality. Pulsed laser welding allows only rather small joint tolerances (max. typical gap 0.15 x thickness, [10]) and is sensitive to residual dirt on specimens before welding. Current specimens were not always cut at right angles and showed sometimes residual dirt, even after ultrasonic cleaning. Improvements have to be made in the area of sample cutting, machining and cleaning to obtain samples of higher quality.

The presented work consists only of double sided welds. This allows to weld relatively thick material before performing all extensive optimization runs on all welding parameters of interest. Weld penetration depth should and can be increased to allow full penetration single sided welding by further optimising of welding parameters. In some cases single sided full penetration welding was obtained.

No surface cracks have been found that could be attributed to the helium content of the specimens. Also, preliminary metallographical results show some cracks in the fusion zone for specimens which did not show surface cracks. This confirms the idea that inspection on surface cracks is useful but not sufficient to judge weld quality.

5. FUTURE WORK

Future work includes improved sample manufacturing and optimization of welding parameters. Also some specimens of stainless steel 316L and Inconel 625, machined at high quality, are planned for irradiation in the HFR.
After optimizing sample manufacture and welding parameters more profound analysis of welded specimens is planned. This includes transmission electron microscopy (TEM) to investigate helium distribution throughout specimens and welded zone, as well as mechanical testing of welded joints - probably a notched tensile test. In parallel, some TEM and low cycle fatigue work is being performed in cooperation with the Efremov Institute (EI), St. Petersburg after TIG, electron beam, and laser welding of cyclotron He-implanted stainless steel [11].

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