ECN WELDING FACILITY FOR IRRADIATED MATERIAL

by

G.L. Tjoa
D.S. d'Hulst
E.V. van Osch
E.W. Schuring
Netherlands Energy Research Foundation (ECN)
Petten, the Netherlands

Paper to be presented at the Plenary Meeting of the
European Working Group
"Hot Laboratories and Remote Handling",
September 21-23, 1998, Windscale - UK

ECN WELDING FACILITY FOR IRRADIATED MATERIAL

by

G.L. Tjoa
D.S. d'Hulst
E.V. van Osch
E.W. Schuring
Netherlands Energy Research Foundation
(ECN)
Petten, the Netherlands

ABSTRACT

During the operational life of future fusion machines, like ITER and DEMO, remote repair, maintenance, and replacement of blanket components is foreseen. Welding will play an important role in these procedures.
Further, in current BWR's and PWR's welding of irradiated parts is becoming more important in view of repairs and refurbishments.
Unfortunately, welding of neutron irradiated and helium containing stainless steel is complicated by the higher sensitivity to weld cracking in the heat affected zone and fusion zone. Usually, this is attributed to the presence of helium, which is formed by transmutation reactions in the material.
In the framework of the European Fusion Technology Programme, ECN carries out investigations on the weldability of neutron irradiated stainless steel. Investigations are being done with pulsed laser welding and tungsten inert gas (TIG) welding techniques.
This paper describes both the laser and TIG welding facilities, which are installed in the ECN Hot Cell Laboratories. Further, an impression is given of the current laboratory practice along with an overview of some recent results.

INTRODUCTION

During the life of a fusion machine certain components will have to be replaced. Replacement of nuclear components implies that irradiated materials have to be welded. Also, repairs and maintenance in currently operating BWR's and PWR's requires welding techniques to be used. Unfortunately, welding of neutron irradiated steel is complicated by the higher sensitivity to weld cracking. Cracking often occurs in the heat affected zone (HAZ) and/or in the fusion zone, and is usually attributed to the presence of helium. Helium is formed by transmutation reactions in the steel.

In the framework of the European Fusion Technology Programme, ECN carries out investigations on the weldability of neutron irradiated steels. Investigations are done with pulsed laser welding and tungsten inert gas (TIG) welding techniques [1-3].

For the ITER Programme this concerns austenitic stainless steel 316L(N), whereas the weldability of irradiated reduced activation martensitic steels (8-9% Cr steel) is investigated in the EU Long Term Fusion Materials Programme. Emphasis is given to a qualification and rough quantification of the embrittlement phenomena of irradiated structural steels by using the welding techniques followed by metallographic and mechanical examination. Therefore, after the welding experiments specimens can be machined by using the same laser equipment or by conventional machining techniques to obtain the mechanical properties of the joints. In this respect, reconstitution of tested samples is also foreseen in the future. The welding techniques are successfully applied for rewelding irradiation capsules.

This paper covers the development and installation of both the TIG and laser welding facilities, which are installed in the ECN Hot Cell Laboratories. Further, an impression is given of the current laboratory practice along with some recent results.

FACILITY

The TIG welding and laser welding equipment is installed in a lead shielded medium activity cell of the ECN Hot Cell Laboratories. Schematic drawings are given in Figures 1 to 3 respectively.

The present set-up allows for welding of flat specimens. Precautions are made to prevent contamination of the cell by volatile and aerosol welding products.

TIG WELDING EQUIPMENT

The TIG welding installation consists of the following components.

Power supply	Dimetrics Inc, type CENTAUR 150PTW
Current supply	100 A max continuous direct current
Pulse frequency	100 Hz max
Pulse current	150 A max
Welding speed	Up to 300 mm/min at max travel length of 80 mm
Arc length control	Dimetrics Inc, Auto Voltage Control (AVC) System

The equipment is fixed on a mounting frame and further consists of an X-Y table and clamping device. The X-slide of the table controls the welding speed, whereas the Y-slide primarily serves as a pre-positioning alignment tool before welding starts. The clamping device is water cooled and contains connections for gas shielding and the ground lead for the arc current. Cooling of the clamping device ensures reproducibility of the welding conditions when large series of welding experiments are performed.

The welding power supply is computer controlled and offers data logging and error detection as well as storage and retrieval of welding programmes. The welding torch is water cooled and contains a non-consumable W-2%Th electrode with an axially ground tip. During the process the weld is shielded by argon or helium, of which the flow rate is between 2 and 20 l/min.
The power supply is placed outside the hot cell.

A schematic drawing and a picture of the set-up are presented in Figures 1 and 2.

X LASER WELDING EQUIPMENT

The basis of the laser welding equipment is a pulsed Nd:YAG laser, manufactured by LASAG. The laser head has been completely modified in-house for improved parameter control and beam alignment as well as for multi purpose use. Furtheron, the laser head has been adjusted in order to enable the use of fibre optics, supplied by HAAS. The length of the fibre is 15 metres and has a core diameter of 600 μm. This type of fibre is chosen for its modular composition. In this way the fibre out-coupling optics and the focussing lens can be separated to a distance of more than 300 mm, sufficient for penetration through the 7" lead wall of the hot cell. In the current set-up only a deflection mirror, the 100 mm focusing lens, and a protecting window are installed inside the hot cell. This results in a minimum number of optical components that are exposed to γ-radiation.

Specimen alignment and visual inspection of the weld is done by a CCD camera, which is mounted outside the hot cell. The camera views the weld surface through the optics that are used for the laser beam focussing.
In addition the laser beam can be connected to several experimental set-ups for different applications such as
- the measurement of thermal diffusivity, through an optical fibre to an in-cell set-up;
- a laser cutting head, to machine mechanical testing specimens after welding.

A schematic of the laser welding equipment in the hot cell is given in Figure 3.

In summary the laser welding equipment has the following specifications.

Laser system	LASAG KLS-311/321
Laser medium/wavelength	Nd:YAG/1.064 nm
Pulse duration	0.1-20 msec
Pulse energy (max)	3-70 J (0.2-10 msec), 30 J (20 msec)
Peak pulse power	6-10 kW
Max. average laser power	260 W
Beam diameter	6-12 mm (unfocussed)
Applicable peak power density	50 GW/m^2
Applicable peak energy density	100 MJ/m^2

SPECIMENS FOR WELDING EXPERIMENTS

Specimens for welding experiments can be obtained either by machining them from previously irradiated material, such as left-over CT samples, or by irradiating ready-for-use welding specimens.
Both production routes are being used at ECN, however the latter is preferred because it is difficult and time-consuming to machine specimens of acceptable dimensions and tolerances from irradiated material.

Ready-for-use specimens, also called coupon type samples, are irradiated in the HFR. Stacks of coupons are included in several irradiation capsules, with various target doses and temperatures. The target doses range from 0.5 to 10 dpa, whereas the irradiation temperatures are in the range from 80°C to 300°C.
These specimens are mainly type 316L(N) and reduced activation martensitic steel.
The coupon dimensions are:

LxW (mm)	Thickness (mm)
26 x 24	1 and 1.5
29 x 27	1, 3, and 5

The 5 mm samples are provided with a 3.5 mm deep Y-type groove as shown in Figure 6. Larger samples are obtained from 10 mm thick CT specimens.

Specimens fabricated from previously irradiated CT samples are produced by cutting slices with thicknesses ranging from 1 to 4 mm from the CT-specimens (Figure 4). Subsequently the slices are milled plan-parallel and burr-free, usually to obtain samples with dimensions of 26 x 12 mm, and thicknesses of 1 to 3 mm. These specimens are mainly type 316L(N).

Two samples are butt-welded as indicated in Figure 5. After welding and visual inspection flat tensile specimens can be cut by laser from the joint as projected in the same figure.

WELDING EXPERIMENTS

The objectives of the first welding experiments were to test the functionality and compatibility of the in-cell facility, to find the optimal welding conditions to obtain good welding quality, and to produce reproducible results. The optimised welding parameters are used as a starting point for the experiments on irradiated stainless steel. The indication of the weld quality is obtained by macroscopic examination of the surface and through plate welding (visual, SEM), and microstructural investigation (SEM, microscope).
During the experiments a wide range of welding parameters are monitored. TIG weld parameters are monitored by the computer controlled weld current source and automatic arc voltage control. The latter is to achieve a remote controllable arc length control.
The most relevant laser weld parameters are speed, pulse frequency, pulse duration, pulse energy, focus distance, and gas flow. These parameters are obtained by an extensive number of trials.

The following welding experiments were executed.

	TIG welding	Laser welding
Material	Irr. and unirr. type 316L(N)	irr and unirr type 316L(N)
Thickness	1 to 5 mm	1 mm
Weld geometry	butt and Y-type	Butt
	Bead-on-Plate (BOP) welds*	BOP
Welding config.	2 unirr. plates,	2 unirr. plates,
	Irr. (2 dpa) to unirr. plates,	Irr. (0.5 dpa) to unirr. plates,
	Irr. (5 dpa) to unirr. plates	Irr. (5 dpa) to unirr. plates

This paper is limited to results on irradiated Type 316 stainless steel, although some results are available on the reduced activation material as well.

* BOP welds are simulation welds, directly laid down on the plate material, without a joint.

WELDING RESULTS

Optimisation

Good workshop practice and experiences with both TIG and laser welding techniques was the starting point for the optimisation of the welding conditions. Optimised welding conditions for both techniques are categorised in terms of heat input. TIG parameters are determined resulting in the lowest heat input and good welding joint quality. In practice the voltage, current, welding speed, and pulse width are defined to be the parameters. These parameters are varied during the optimisation period over a wide range.

The first laser welding experiments were weld simulations in plate material, so-called Bead-On-Plate (BOP) welds. Since laser welding is by nature characterised by its low heat input, combinations of specific parameters are investigated as mentioned. Next, welding experiments were performed to join unirradiated to irradiated samples.

After each weld a visual examination was performed based on the following criteria: surface appearance must be regular and shall have no or limited discoloration, whereas the through plate penetration shall be good and complete. Next, samples were selected to investigate for macro and micro cracks, overall structure, hardness profile, etc.

TIG Welding Results

The 1 mm weldments were made without filler material and show a smooth surface on both sides. The microstructure of the weld metal was austenite with a dendritic network of δ-ferrite, showing a directional solidification towards the weld centre.

The 4 mm weldments were made to determine the maximum thickness for a single pass through plate welding. The current set-up allows for through plate weldings of 4 mm plate, although it requires welding currents close to maximum capacity of the welding power supply. Single pass through plate weldings are therefore limited to 3 mm plate thicknesses.

The 5 mm plates were provided with a Y-type groove and the weldments were multi-layer (4-6) welds. In the HAZ a narrow grain growth zone was found.

All weldments (1 to 5 mm thicknesses) of <u>un</u>irradiated material are free from hot cracks and other welding defects. δ-Ferrite was found in all weldments of which the volume percentage increases (7 to 10%) with increasing thicknesses. Examples are given in Figures 7 and 8.
Hardness measurements show a slight hardness increase in the weld with respect to the base material (Figure 9). This is probably caused by restraint of the specimen.
The weldments of <u>ir</u>radiated 316L(N) did not show significant external defects in non-destructive testing (visual, SEM, X-ray). However some defects, similar to hot-cracking, were found in the first available cross sections. Further destructive examinations are continuing.

Laser Welding Results

The laser weldments were mostly joints of unirradiated to irradiated samples. The target doses of the irradiated samples range from 0.5 to 5 dpa, resulting in an equivalent He content of 7 to 30 appm respectively. The first series of weldings include 12 samples with 0.5 dpa and 8 samples with 5 dpa irradiation damage.

Visual and SEM examinations show that all welded joints surfaces were smooth. External defects were not found neither in the fusion zone nor in the HAZ. Also no defects were found by radiographic inspection.

In general, no large cracks or pores were found by the microstructural examinations in the welded joints of 0.5 dpa irradiated to unirradiated samples. Small hot cracks were found on the fusion line, whereas the HAZ is free from intergranular cracks.
In both the 0.5 and 5 dpa samples hot cracks were concentrated on the fusion line of the irradiated material.

Hardness measurements (HV 50 g) were performed to determine the width of the HAZ and the influence of the welding on the hardness of the irradiated material. Hardness profiles were made running from the irradiated material into the unirradiated base material.

SUMMARY

A shielded TIG and laser welding facility for welding experiments on irradiated steel is successfully installed in the Hot Cell Laboratories.

Sound laser welded joints were made of irradiated (dose corresponding to 30 appm He) to unirradiated stainless steel Type 316L(N).
Minor hot cracks were found at the fusion line in the irradiated material.

TIG welding of unirradiated Type 316L was successfully performed on plate thicknesses from 1 to 5 mm.
Optimised TIG welding conditions were defined in terms of heat input.

TIG welds o funirradiated material show smooth surfaces without hot cracks. No micro or macro cracks were found by microscopic or radiographic examinations.

Recently, TIG welded joints on 1, 3, and 5 mm Type 316L(N) irradiated
(2 dpa) coupons are made and no surface defects are found. Metallographic examinations are now being performed.

Hardness measurements of the TIG joints show a slight hardness increase in the weld compared to the base metal. In the laser welded joints there is a tendency that the HAZ width is influenced by the heat input, e.g higher heat inputs lead to wider HAZ.

With the welding facility machining of mechanical testing samples is possible, whereas rewelding of irradiated capsules in the frame of Recycling Actinides and Fission Products experiments is also successfully applied.

REFERENCES

[1] E.V. van Osch, D.S. d'Hulst, and J.G. van der Laan, "First Results of Laser Welding of Neutron Irradiated Stainless Steel", ECN Report ECN-RX--94-074, October 1994;

[2] E.W. Schuring, D.S. d'Hulst, and E.V. van Osch, "Laser Welding of Irradiated AISI 316L(N)-ERHII 1 mm Plate", ECN Report ECN-C--98-043, March 1998;

[3] E.W. Schuring, D.S. d'Hulst, and E.V. van Osch, "TIG Rewelding Facility in ECN Hot Cell Laboratory", ECN Report ECN-C--98-044, March 1998.

FIGURES

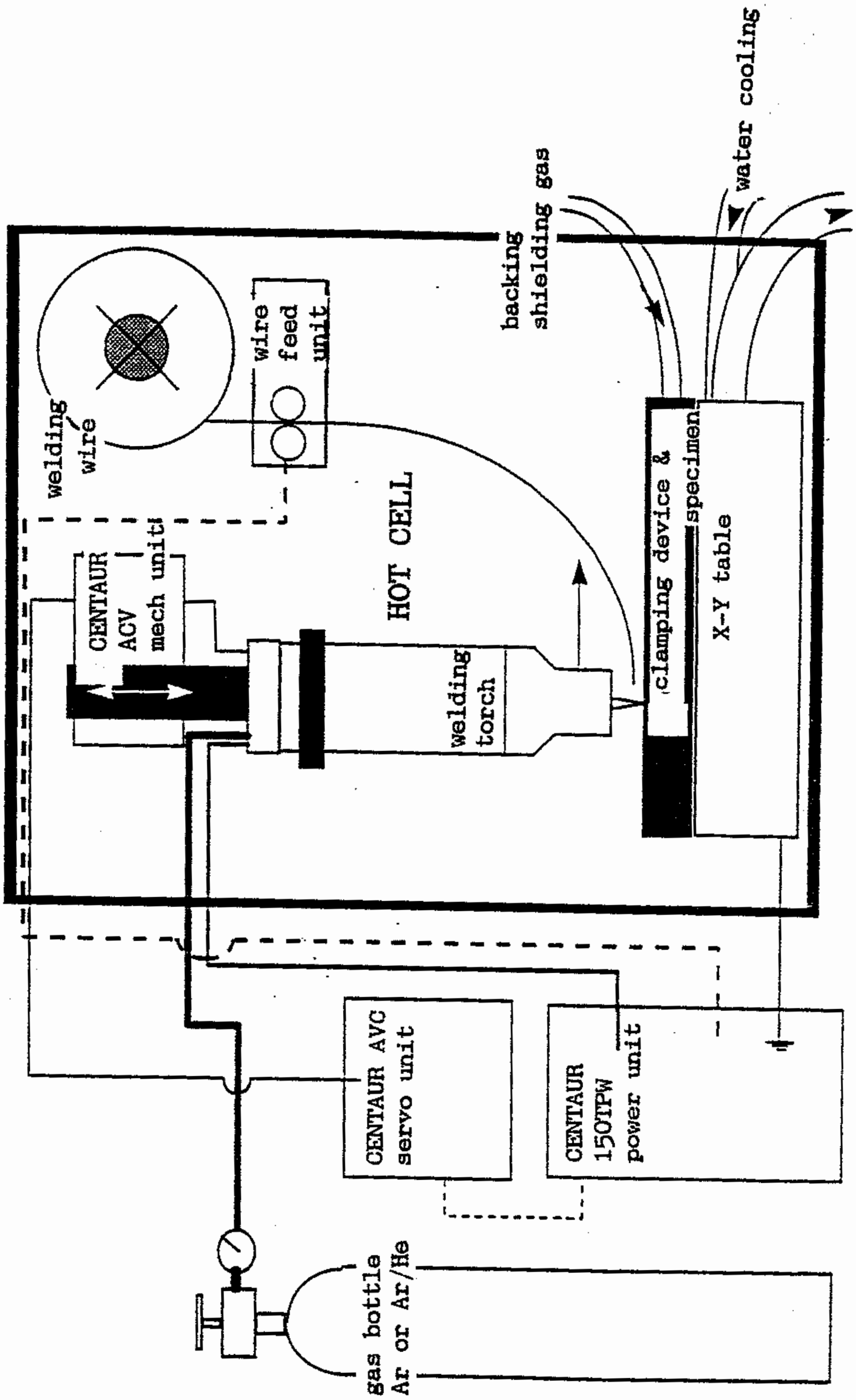


Figure 1 Schematic presentation of the TIG welding facility.

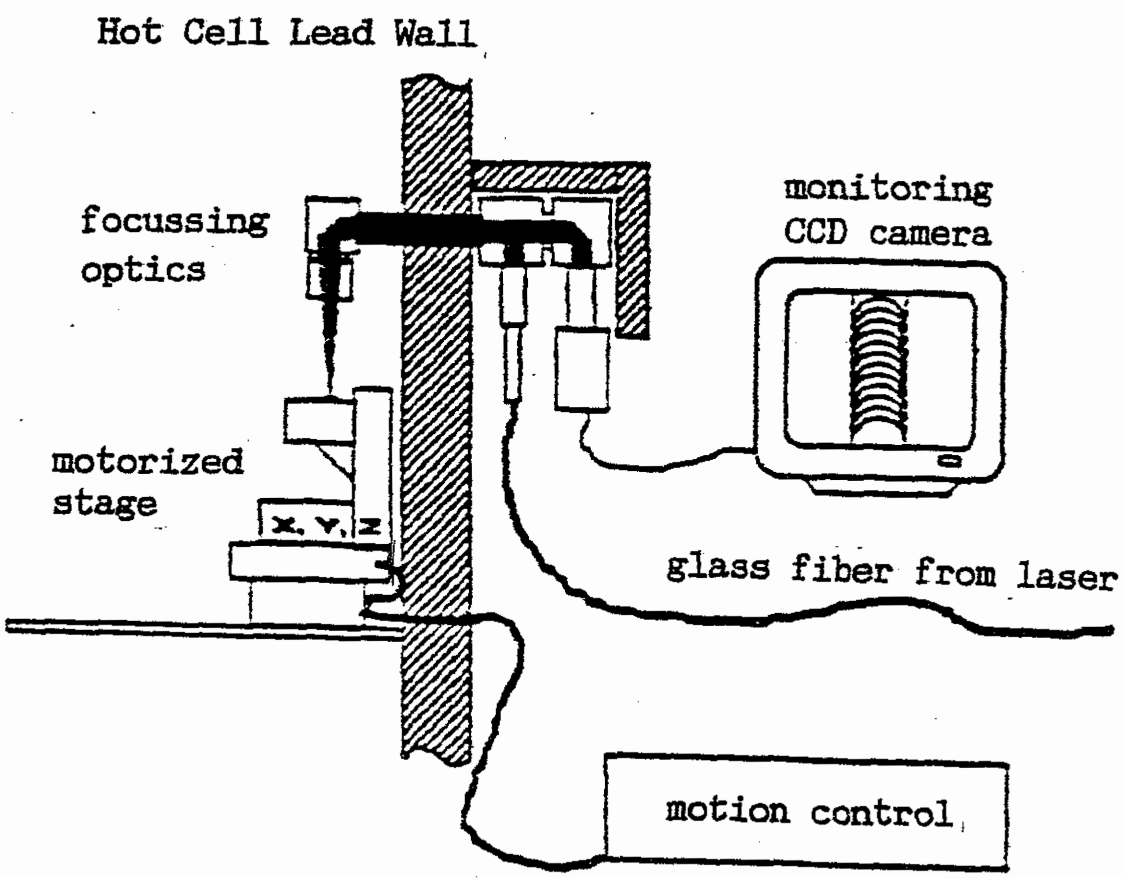
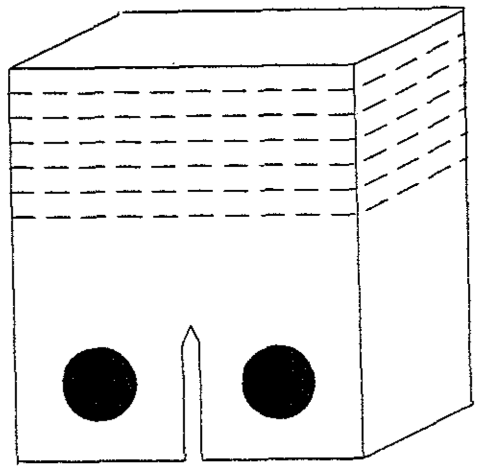


Figure 3 Schematic set-up of the laser welding equipment in the hot cell.



samples from CT type

Figure 4 Cutting scheme for sampling of welding samples.

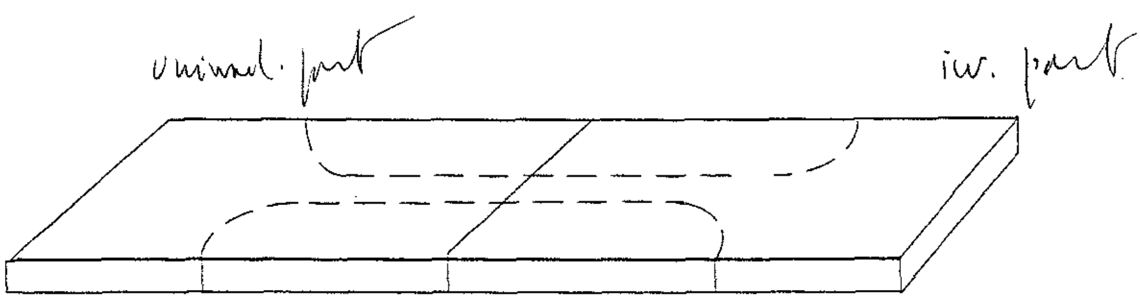


Figure 5 Schematic of butt-welded joint and projected flat tensile specimen.

also laser welding

1 / 3 / 5 mm
thick samples

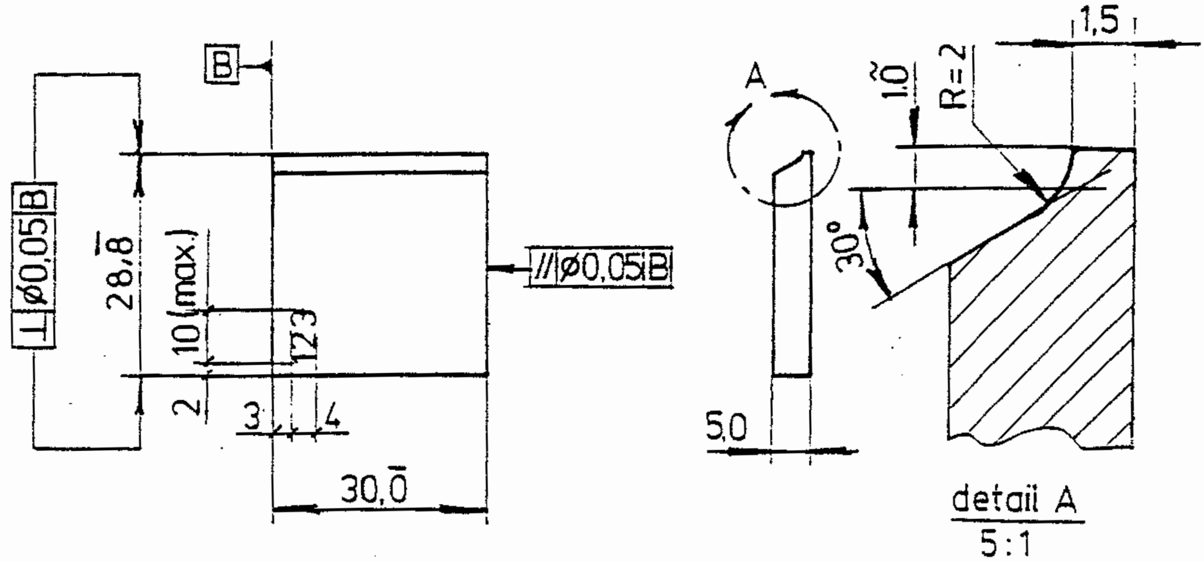


Figure 6 Dimensions of Y-type groove for 5 mm samples.

considering the thickness

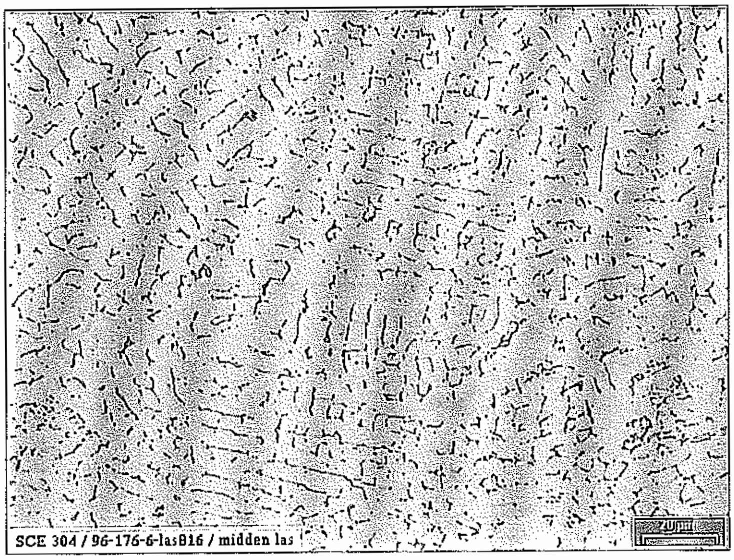


Figure 7 δ-Ferrite distribution in a 1 mm thick welded joint (unirradiated).

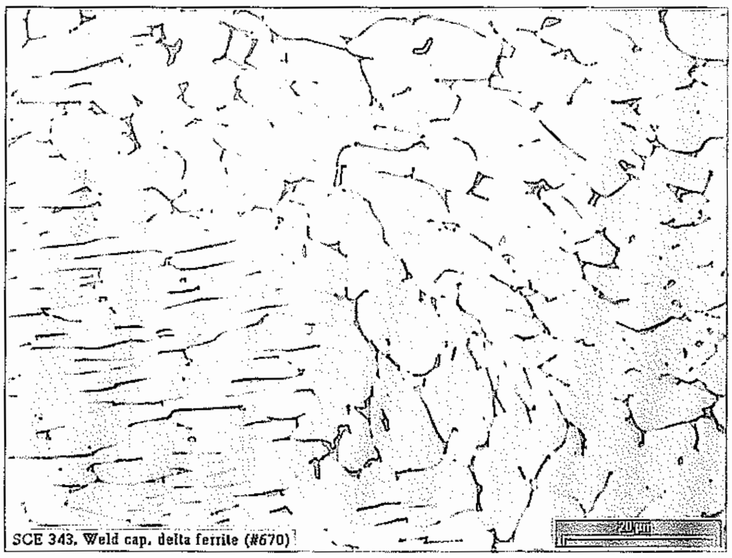


Figure 8 δ-Ferrite distribution in a 5 mm thick welded joint (unirradiated).

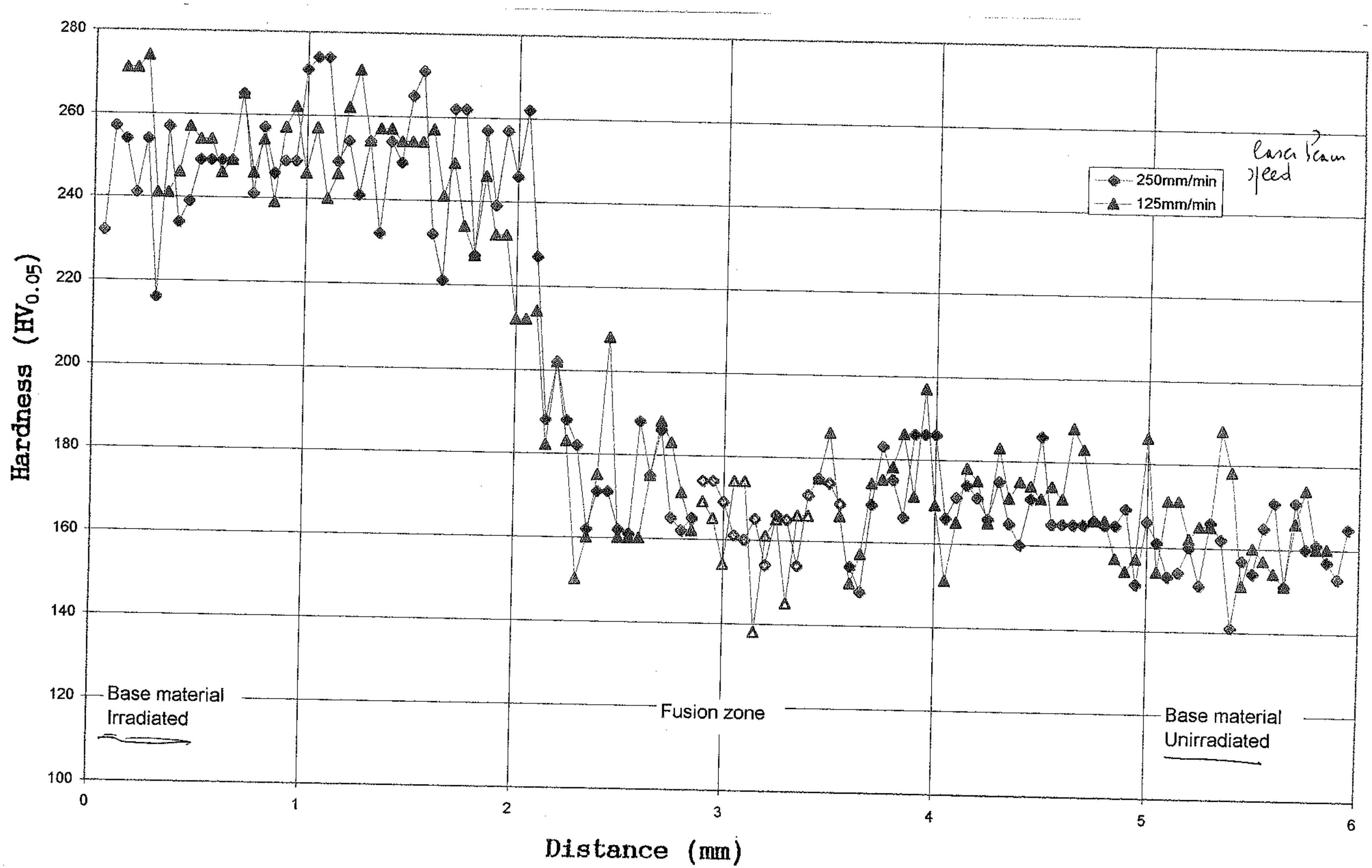


Figure 9 Micro-hardness ($HV_{0.05}$) profile in a laser welded joint, 5 dpa irradiated.