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RECONSTITUTION OF CHARPY-V NOTCH IMPACT SPECIMENS FOR THE PRESSURE VESSEL STEEL SURVEILLANCE

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TABLE OF CONTENTS

ABSTRACT

With the main purpose of increasing the number of Charpy-V notch specimen test results generated from a typical pressure vessel steel surveillance programme, an experimental project, supported by the Belgian utilities, was started to develop a method for retesting broken Charpys.
Based on an EPRI programme for the reconstitution of Charpy specimens by welding techniques, we adapted an arc stud welding process for producing reconstituted specimens.
The system, foreseen for hot cell application, welds studs to both ends of a pre-machined Charpy half specimen.
The experimental results, obtained up to now on unirradiated material, show to be in good agreement with original tests.
The arc stud welding procedure can therefore be used to obtain supplementary toughness data.

INTRODUCTION

During the last few years, a progressively increasing part of our hot cell operations has been devoted to the pressure vessel steel surveillance (PVSS) programme of the Belgian Nuclear Power Stations. With seven units into operation now, we are facing a surveillance capsule examination programme almost every year.

Besides the dismantling of the capsule and identification of the steel specimen train, the main part of the hot cell operation campaign is related to the mechanical testing of the reference steel samples and dosimetry analysis, imposing a hot cell load of about 750 man-hours.

Static tensile- and dynamic impact tests are the principal analysis to be performed in order to demonstrate the neutron embrittlement of the pressure vessel material.

The neutron embrittlement of the material is principally demonstrated by the increase in the transition temperature from ductile to brittle behaviour and a decrease of the upper shelf energy both evidenced by the conventional impact test.

The limited number of Charpy-V specimens, included in these surveillance capsules, to monitor the changes in toughness of the vessel steel, is sometimes insufficient for the complete establishment of the transition curve with a certain degree of accuracy.

Now, supplementary toughness data can be obtained by reconstituting fractured Charpy-V specimens and performing additional tests on such specimens.

WELDING PROCEDURE

The main parameters which in general terms have to be considered in the selection of a suitable welding technique for specimen reconstitution are :

- quality of the weld
- width of the heat-affected zone
- loss of specimen material at welding
- welding time and heat build-up in the specimen
- possibility for remote handling and overall dimensions for hot cell use
- costs involved.

Based on an EPRI report concerning the reconstitution of Charpy impact specimens [1], and after a limited practical study on different welding procedures by our general workshop department [2,3], projection welding and stud welding seemed to be the most likely techniques.
For our purpose, an arc stud welding technique was chosen for joining end tabs to broken machined Charpy specimen halves, thereby producing a reconstituted full-size specimen for additional testing.
In this welding technique heat is developed by drawing an arc between the stud (end tab) and the workpiece (1/2 C_v-specimen) to which it is to be welded.
The two pieces are forced into contact when the proper temperature is reached.
Fig. 1 shows the principle of the stud gun welding system.
In the next paragraph a brief description of the welding equipment is given.

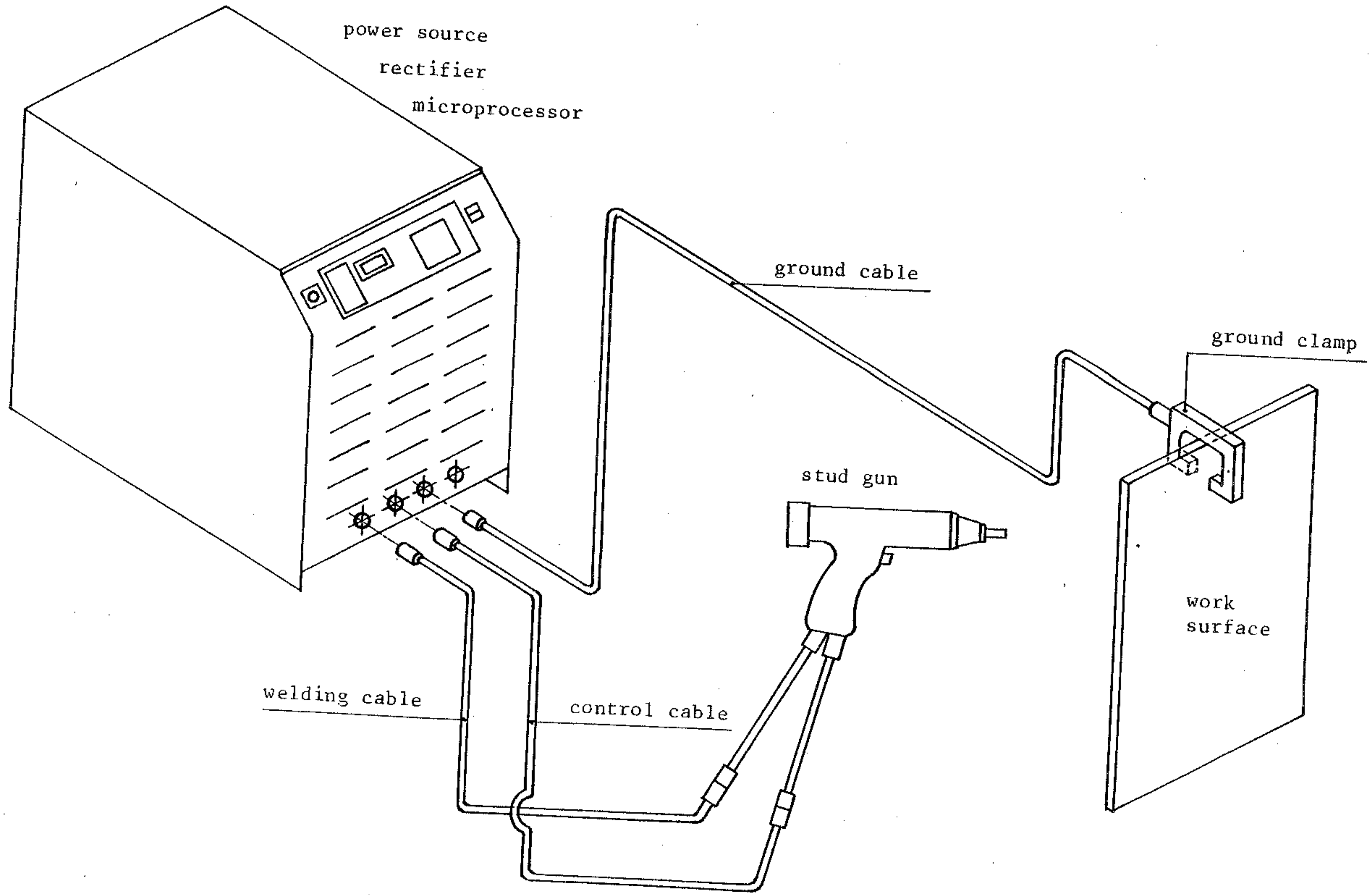


Fig. 1 PRINCIPLE OF THE STUD GUN WELDING SYSTEM

ARC STUD GUN WELDING EQUIPMENT

The arc stud gun welding equipment is composed of the following main elements.

a. Stud gun

- a chuck to hold the stud (end tab);
- a magnetic solenoïd system to lift the spring loaded chuck off the workpiece.

b. Alignment frame

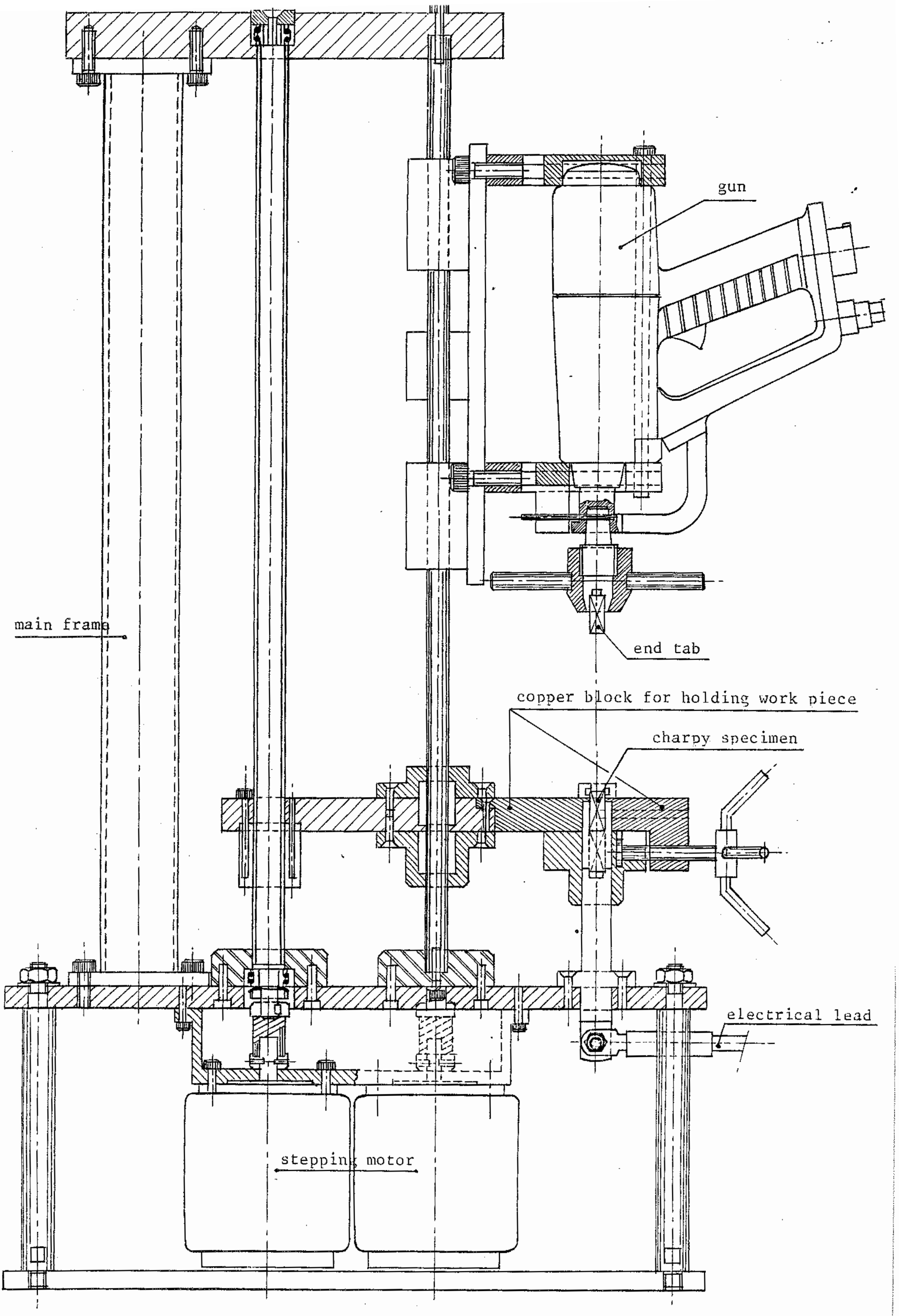
- a ball bushing guided alignment permits the stud gun chuck support to move in a vertical position without excessive lateral movement;
- a stepping motor drive unit for this vertical displacement;
- a support fitted with a copper block for holding the workpiece (specimen half) and a stepping motor drive unit for the vertical displacement of this plate allowing a variety in length of workpiece - end tab combination; this copper clamp serves also as a chill block to minimize temperatures in the workpiece and as the current conductor;
- a plastic hood placed around the stud gun chuck and workpiece fixture in order to have a cover of argon gas avoiding general oxidation.

c. Power supply and controller unit :

- a power unit supplying the high current needed for the arc of the welding;
- controller : a microprocessor-controlled stud welding system with great versatility and reliability (KSM Micromark TM 2000) allowing :
  - precise regulation and duration of weld current;
  - digital verification of all weld parameters;
  - indication of weld and system deviations.

Fig. 2 gives a sketch of the gun and alignment fixture developed for hot cell operation.

Fig. 3 is showing the stud welding power supply and controller unit.



Sketch of Gun and Alignment Fixture

Fig. 2

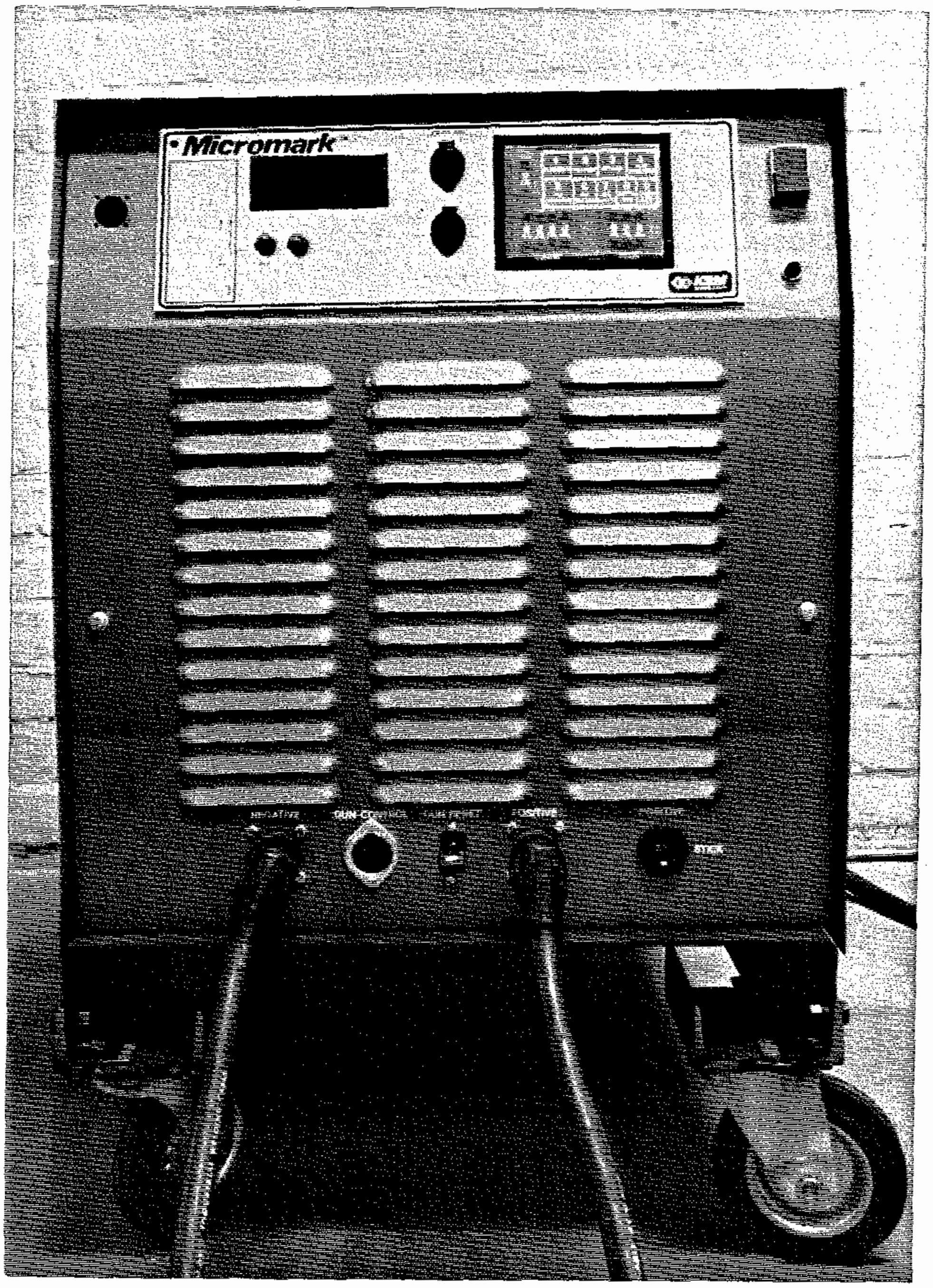


Fig 3. Power supply and controller of stud welding system.

Welding technique

The following phases can be considered in the welding technique.

Preparation

- The weld gun is raised and a stud (end tab) is loaded into the chuck; a small aluminium ball is fixed into a hole on the surface of the end tab acting as initiator for the arc (it also avoids severe oxidation of the molten metal).
- The workpiece (Charpy-machined half specimen) is positioned in the copper chill block clamp; both end tab and specimen are clamped firmly.
- A ceramic arc shield, used to limit the spread of molten metal and of severe oxidation, is positioned around the specimen, and the stud gun is lowered, bringing the end tab into contact with the specimen surface.

Welding

- An automatic sequence welding is started by actionating the gun trigger, hereby the end tab is lifted with respect to the specimen by the action of the electromagnetic coil within the gun body :
    - This causes initiation of an arc between the aluminium ball in the end tab and the workpiece.
    - The arc is sustained for a given time with the stud retracted.
    - At the end of the arc cycle, the power is automatically switched off, the coil is de-energized and by the action of the main spring of the gun the end tab is forced into the workpiece (specimen) with molten surface.

- By this operation, the first end tab is welded to the central part.

The same procedure is to be repeated for welding the second end tab to the other surface of the specimen.

As a result, we obtain the central segment from the original Charpy specimen with end tabs welded to each end.

The next step in the reconstitution of the Charpy specimen is the conditioning of the as-welded unit in machining off the burr created during the weld flash on each of the four surfaces, cutting the specimen to the appropriate length dimension and milling the V-notch in the middle of the specimen.

A compact multi-purpose milling and cutting equipment will therefore be installed in the hot cell.

SPECIMEN SELECTION CONSIDERATIONS

Workpiece

In the selection of the blank specimen (workpiece), a minimum length of material is to be determined depending mainly of the plastic deformation that will exist in the broken half Charpy-V specimen from the original test, the welding process heat-affected zones at both sides of the workpiece near the weld, the annealing area due to the heat generation in the specimen, as well as on the original specimen homogeneities (e.g. base metal in a weld metal coupon).

Our preliminary experimental work of welding studs to ferritic steel samples [2,3] indicated a heat-affected zone expansion during the welding process of about 2 mm at the specimen axis, and, although alignment was not perfect at that time, the spread of this HAZ mounted only to about 6 mm at the specimen surface.

We also controlled the heat generation during the welding process as temperature rise of the workpiece is of critical importance especially in the reconstitution of irradiated material.

Temperature measurements during the welding have been performed by fixing thermocouples in the specimen and recording the temperature as a function of the distance to the weld surface.

At about 2 mm from the weld surface, temperature rise reached about 210°C and decreased to about 100°C at 3 mm and 60°C at 5 mm, demonstrating that at a relatively short distance away from the fusion line, the temperature rests well below normal operating temperature of the reactor, avoiding an annealing out process of radiation damage of the major part of the irradiated material which is to be investigated later.

These first results correspond fairly well with the experimental work sponsored by EPRI at Battelle Columbus Laboratories [4] using the arc stud gun welding, as well as by Westinghouse [5], operating with a similar welding technique, i.e. projection welding.

In our more detailed experimental work, temperature-time controls will be performed by positioning thermocouples at and near the base of the notch of the selected samples.

Considering the different factors involved, one decided to start the qualification work with blank specimens having a length as great as possible. This avoids pronounced deformation resulting from the original test at the specimen surfaces. Specimens that broke at the lower part of the transition curve have less chance, (1) that they are bent and (2) that the plastic zone created in the original test will be to important.

End tabs

The material of the end tabs to be used is also an important factor in the reliability of the reconstituted Charpy impact test specimen.
It is quite obvious that the best choice of material would be to take identical material as the blank specimen to be conditioned. Of course, this is not very evident, and normally we have to consider other materials, especially in the reconstitution process of irradiated specimens were in most cases, unirradiated end tabs, prepared outside the hot cell, will be taken.
In general terms, the end tab material should be of a steel that has good weld compatibility with the specimens material and with similar elastic properties. We will consider this item in detail during our qualification programme; but of even more importance is certainly the alignment of the end tabs on the blank specimen after welding. Twisting of the end tabs must be avoided as good as possible. Special care is therefore given on the fixture of the weld gun on the frame, the vertical displacement of the gun, and especially lateral movement of the gun chuck parts must be out of the question. The absorbed energy of a twisted specimen assembly will certainly be greater than for the original specimen.

SPECIMEN PREPARATION STAGES

After selection of the specimens to be reconstituted, in a first phase these Charpy-V specimens which have been tested in the lower region of the energy transition curve, the fracture surface is machined off as well as the small part of the specimen that deformed plastically in the original test.

When "weld" specimens have to be considered, the initial position in the weld zone of the parent steel plates must be checked. In fact, weld specimens normally available in the pressure vessel steel surveillance capsule have been foreseen initially at different locations over the plate thickness. A macro etching technique is applied in our laboratory [6] for control of the fusion line in the "weld specimen" as well as for identifying the weld half of the "HAZ specimen".

Fig. 4 schematically represents the different stages in the specimen preparation.

After welding operations, the weld beads are removed on each of the four surfaces by a milling apparatus, foreseen for remote handling, using a workpiece holder designed to firmly clamp the specimen. The V-notch in the blank specimen is carried out by the same apparatus using a broach (this operation can also be performed before the welding of the end tabs). Finally the end tabs are cut to the required length using an abrasive cut off wheel.

Fig. 5 is showing this equipment.

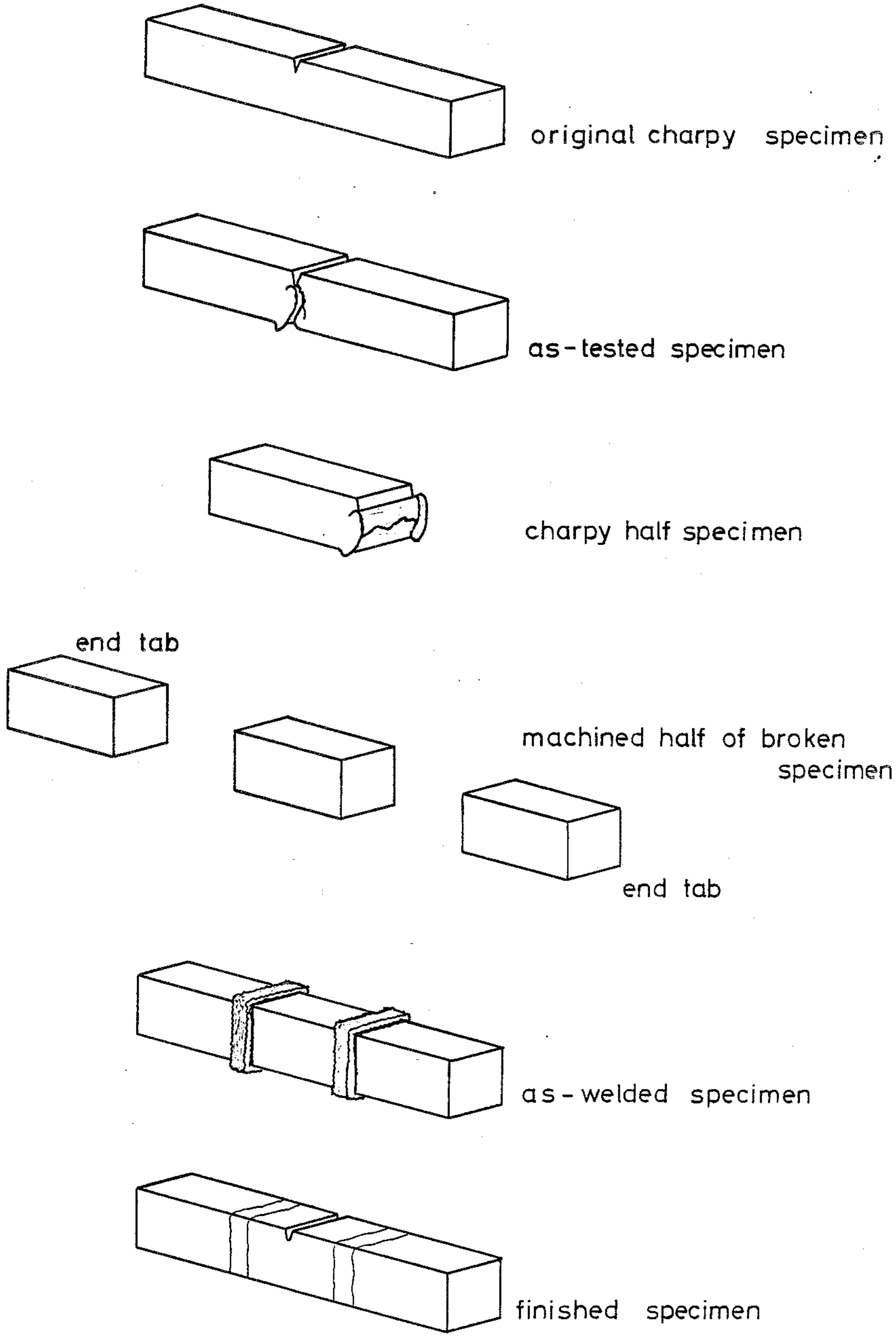


Fig. 4 :Stages in Preparing a Reconstituted Charpy Specimen.

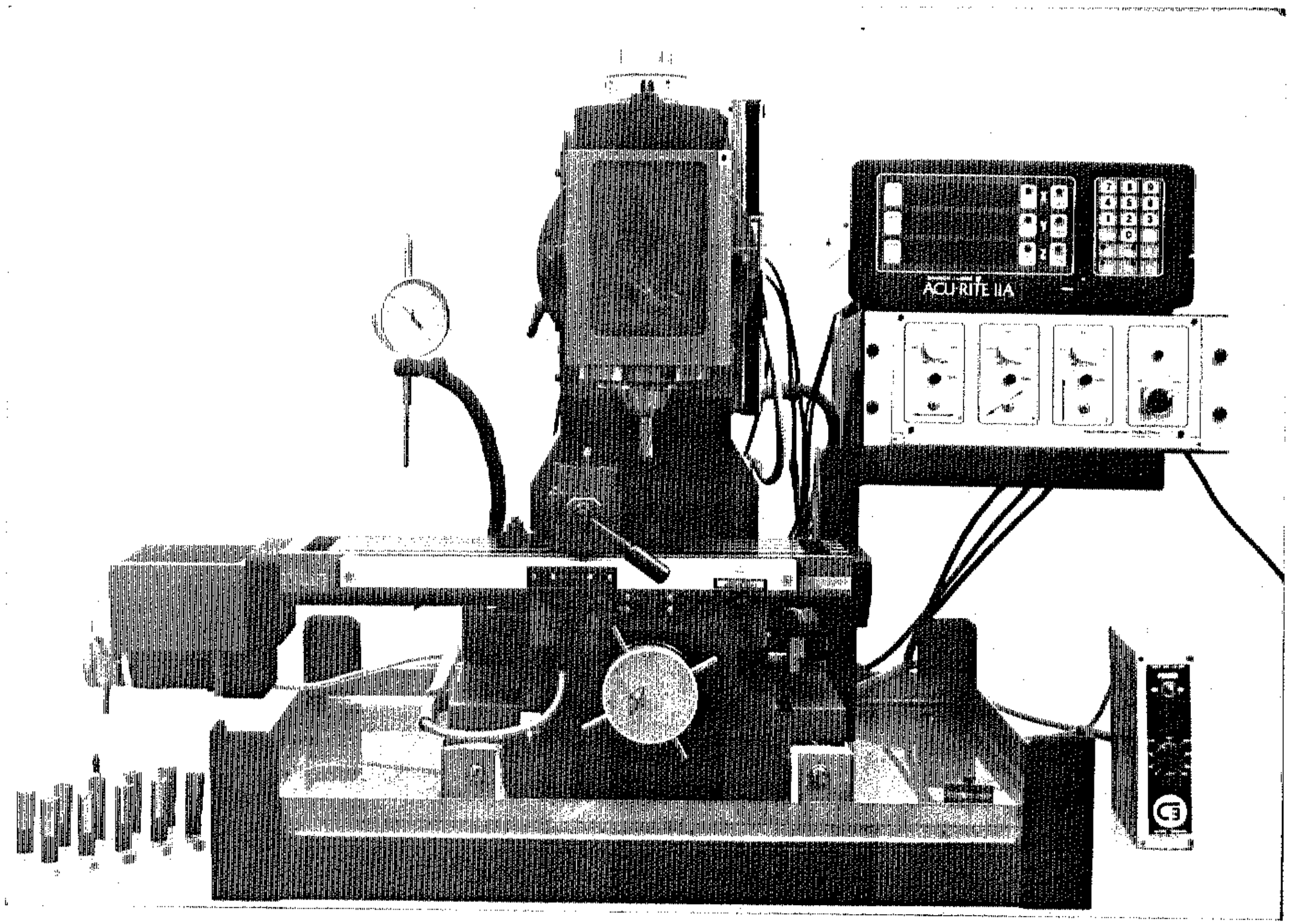


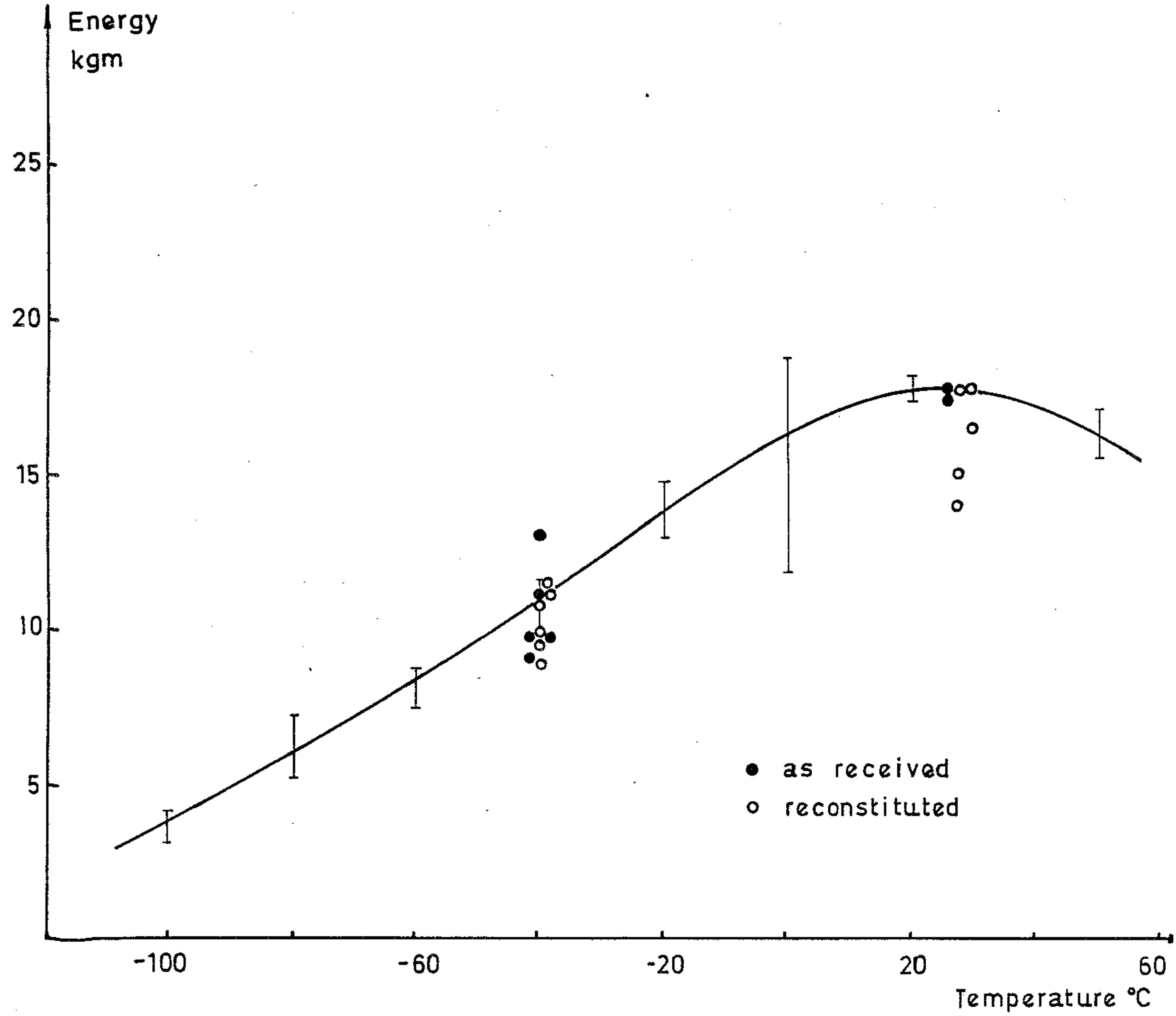
Fig. 5 Multi-purpose Milling and Cutting apparatus

CHARPY-V TESTING OF RECONSTITUTED SPECIMENS

In the first phase of our demonstration programme one has dealt with a reference ferritic steel plate material, the energy-temperature transition curve of which has been established by a Belgian reference laboratory.
The test campaign of the original as well as of the reconstituted specimens has been performed with the instrumented impact test equipment installed in the hot cell [7].
The purpose is of course to control not only the absorbed energy with the possibility of differentiating between initiation- and propagation energy, but also to have evidence of the load behaviour during the impact event with all parameters contributing in the process.
An important factor in this aspect is the influence of the end tabs welding on the compliance of the reconstituted sample in comparison with the original. One discusses this item in more detail when the Charpy test results are interpretered.
In the appendix informations are provided on the compliance calculation.
For the end tabs, studs of the same material were used, avoiding any difference in weld compatibility or elastic properties.

Fig. 6 shows the calibration curve of the plate material, the results of the original specimen tests and the results of the reconstituted specimens.
The test temperatures correspond with those for the original set of specimens, but we have also checked the reliability of the reconstitution process in testing both halves at different temperature after welding.

Table 1 is grouping our principal results for this campaign.
Even though we observed some porosity in several weld regions of the reconstituted specimens, all the specimens fractured in the V-notch and the data are in the normal engineering scatter band for Charpy test data.



IMPACT CALIBRATION CURVE SOUDOTENAX 56 PLATE 46 mm

FIG. 6

Table 1. Reconstitution of C_v specimens - Impact test results

Material : Soudotenax 56. Plate 46 mm. FS10. CRM

Specimen	Temp. °C	Energy J	Reconst.	Temp. °C	Energy J	Reconst.	Temp. °C	Energy J
FS108	25	175	A	25	174	B	25	176
FS1038	25	171	A	27	146	B	-40	106
FS1059	-40	96	A	-40	87.5			
FS1047	-40	89	A	-40	97	B	27	136
FS106	-40	128	A	-40	114	B	27	147
FS1018	-40	96.5	A	-40	113			
FS1030	-40	109	A	-40	109	B	29	161

Despite this relatively good correspondence, it is interesting to consider more in detail these results.

Table 2 gives an analysis of the tests starting from the oscillographic records of the instrumented impact apparatus.

Table 2. Analysis of Charpy tests

Specimen	Test Temp.	Dial Energy	Integrator Energy (uncorrected)			Load		Time		Apparent Deflection		Total Compliance
		E_d	E_T	E_I	E_P	P_{GY}	P_M	t_{GY}	t_{max}	d_{GY}	d_{max}	C_T
	°C	J	J	J	J	kN	kN	ms	ms	mm	mm	mm/kN
1. FS108 "as-received"	25	175	178.8	60.6	118.2	10.9	16.0	0.18	0.97	0.93		8.5×10^{-2}
A - reconstit.	25	176	178.8	54.5	125.5	11.2	15.5	0.15	0.91	0.78		8.6×10^{-2}
B - reconstit.	25	174	169.8	54.5	115.3	10.7	15.8	0.18	0.85	0.93		8.7×10^{-2}
2. FS1030 "as-received"	-40	109	109.2	55.8	53.4	11.6	16.5	0.13	0.82	0.68		5.85×10^{-2}
A - reconstit.	-40	109	109.7	48.5	61.2	11.6	16.2	0.13	0.79	0.68		5.85×10^{-2}
3. FS1038 "as-received"	27	171	169.7	57.6	112.1	9.9	15.8	0.18	1.0	0.93		9.37×10^{-2}
A - reconstit.	27	146	145.8	57.6	88.2	9.2	14.1	0.12	0.85	0.62		6.73×10^{-2}
4. FS106 "as-received"	-40	128	128.4	54.5	73.9	11.6	16.5	0.15	0.82	0.78		6.7×10^{-2}
A - reconstit.	-40	114	114	57.0	57.0	11.6	16.5	0.15	0.82	0.78		6.7×10^{-2}

List of symbols (ref. Table 2)

- E_d : dial energy ; energy recorded on pendulum dial.

- Integrator energy : energy obtained from the integrated load-time signal uncorrected for velocity reduction and electronic decay.

with

E_T : total fracture energy

E_I : initiation energy (uncorrected for machine energy)

E_P : propagation energy = $(E_T - E_I)$

- Load

P_{GY} : general yield load

P_M : maximum load

- Time

t_{GY} : time to reach general yield

t_{max} : time to reach maximum load

- Apparent deflection

d_{GY} : apparent deflection at general yield

d_{max} : apparent deflection at maximum load

- Total compliance C_T : total system compliance

= $(C_S + C_M)$

C_S : specimen compliance/C_M machine compliance

The first sample set presented in the table could be described as being very good, i.e. the energy data fit quite well and the welding process kept the total compliance almost unchanged.
For the second sample set, tested at low temperature, the data of the reconstituted sample are in fact perfect; but for the third sample however, we observe a relatively large difference in the energy data as well as for the total compliance, indicating that the welding of the end tabs has changed the specimen compliance, considering that the machine compliance is the same for both original and reconstituted specimen.
Of course, compliance in not the only factor involved in the reconstitution procedure as is evidenced by the data of the fourth specimen set, indicating a decrease in dial energy with an unchanged total compliance. This is rather surprising and cannot be due to misalignment or twisting of the specimen parts or to uncomplete welding as these effects would have increased the absorbed energy.

Materials which will be considered further in the qualification phase are :

- sets of Watertown Arsenal calibration Charpy specimens
  AMMRC
  - low energy range : ± 16 J
  - high energy range : ± 95 J

- sets of broken reference material - plate & weld
  "acier Cockerill GV"

- sets of aged specimens of a reactor surveillance programme.

The programme foreseen on irradiated materials will deal with broken Charpy-weld specimens out of reactor surveillance capsules, as well as pressure vessel reference material irradiated at accelerated fluence rate.

COMMENT

Our investigation with the arc stud gun welding equipment for the reconstitution of broken Charpy-V impact specimens, up to now, has shown to produce similar results as the original specimen data when a number of parameters are considered in the choice of the blank specimen length and end tabs material.
In the qualification programme, attention will be given on the weld parameters involved, the heat generations in the blank sample near the notch and especially on the alignment of the end tabs on the specimen, and the choice of material in relation to the irradiated specimen campaign. In a first selection of suitable broken Charpy specimens, we will be dealing with specimens that broke at low energy i.e. without any bending and with a minimum amount of lateral expansion at the broken surface.
This programme will be run on reconstituted specimens of qualified material prepared partly outside the hot cell as well as with the complete equipment installed in the hot cell.
Finally, irradiated broken Charpy specimens will be considered for reconstitution.
We hope to get more detailed information before the end of this year.

ACKNOWLEDGMENTS

The authors are greatly indebted to all the persons of the SCK/CEN who have been helpful in the initial phase of the programme.

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LIST OF FIGURES

APPENDIX

Instrumented impact oscillographic test record

The load values usually measured for fracture toughness and strength calculations from the load-time signal are P_{GY} (general yield load) and P_M (maximum load).

Apparent deflection* : product of the average tup velocity $\overline{V}$ and the specific times as measured on the oscillographic record;

- deflection values : d_{GY} and d_{max} with :

$$d_{GY} = \overline{V}\, t_{GY} \text{ and } d_{max} = \overline{V}\, t_{max}$$

by definition : $\overline{V} = V_o(1 - \frac{E_i}{4E_o})$

with V_o the initial velocity prior to impact, E_i the absorbed energy, E_o the total available kinetic energy.

Compliance C : C = d/P deflection divided by load (reciprocal of stiffness)

- total compliance of the system
  C_T = either d_{GY}/P_{GY} or d_{max}/P_M

  and $C_T = C_S + C_M$

  specimen compliance (C_S)
  machine compliance (C_M)

- specimen compliance C_S can be calculated from the specimen geometry and crack depth;

In non-dimensional units, the following expression is normally used :

$$E.B.C_S \text{ or } E.B.d/P = f(\frac{a}{W})$$

with E Young's modulus, B thickness of specimen, W width of specimen, a being the depth of the notch;

- machine compliance C_M

$$C_M = C_T - C_S$$

by knowing C_M, the specimen initiation deflection and true initiation energy can be calculated.