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METHODOLOGY FOR THE ULTRASONIC TESTING OF AUSTENITIC STAINLESS STEEL

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Methodology for the Ultrasonic Testing of Austenitic Stainless Steel

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ABSTRACT

In spite of the many difficulties associated to the propagation of elastic waves by the metallurgical structure of austenitic stainless steel, experience shows that ultrasonic examination can provide in many cases key information as to the integrity assessment of industrial components made from such materials.

The propagation of elastic waves is strongly disturbed by the coarse-grain structure, which may, in addition, vary significantly from place to place in the metal volume to be inspected. Practically, it follows that, to prepare an examination, every case must be presumed peculiar, and careful attention must be paid to any factor that may influence the final result. Achieving such an exploratory study will often lead to a drastic enhancement of the examination capability.

The paper outlines that approach, and illustrates through some examples the extent to which it has been made possible to optimize the actual inspection capability. Directions for future efforts are suggested, where further investigations appear necessary.

1 INTRODUCTION

It is common sense today to declare that the Non-Destructive Evaluation of austenitic stainless steel is a tough business. If still necessary, the results of some demonstration exercises [1,2] organised in the last years, with realistic steel samples, highlighted crudely the severe limitations of ultrasonic testing, as it is commonly implemented. In addition, it may be worth noting that several advanced techniques did not come up with the same performance improvement as on carbon steel.

On the other hand, field experience demonstrates that ultrasonic examination can provide in many cases valuable, if not totally satisfactory, results, if the possibility is given to investigate adequately the examination conditions.

In every NDT application, indeed, the inspection quality that can be eventually achieved depends on the characteristics of the material to be examined, on the inspection method and equipment, and on the skill of the involved personnel. As a general rule, austenitic stainless steel ultrasonic testing requires using all available resources of the current technology, and hence all of the abovesaid contributions must be paid careful attention when preparing and performing an inspection.

2 MATERIAL CHARACTERISTICS

The macrostructure of stainless steel is obviously the one limiting factor, which makes that the austenitic material UT capability will never equal that of ferritic carbon steel.

The ratio between the austenitic grain size and the acoustic wavelength can be so large that the anisotropy of the elastic wave propagation in the crystallographic lattice may no more be neglected [3,4] : the dependence of the phase velocity on the orientation and the existence of preferred propagation modes and directions are direct consequences of that anisotropy. Such phenomena are however not apparent in equiaxed structures, because the influences of randomly oriented crystallites interfere destructively. Besides, the strong scattering encountered in the crystal structure and the acoustic mismatch at grain boundaries tend to transform shortly the ultrasonic signal into diffuse energy.
Finally, the macroscopic inhomogeneity of the components to be inspected cause the steel structure and the associated phenomena to vary from place to place.

In the usual UT-language, those various phenomena can be translated as beam skewing and distorsion, high background noise, false call, uncertainty on the propagation velocity and lack of reproducibility. Flaw detection, location and sizing capability is obviously affected.

The influences of grain size and orientation on sound propagation have been rather extensively studied in both theory and practice : the current state-of-the-art is able to provide guidance as to parent metal elaboration, welding procedure selection and component geometric design, in view of facilitating subsequent UT examinations [5,6]. In the common ISI business of existing plants, however, the chemical contents, heat processings, welding procedures and the resulting metallurgical textures are in most cases poorly documented, the geometry of the scanning areas is far from ideal, and the hidden surfaces are unreliably described. Methods exist to characterize grain structures [7,8], but their applicability is considerably reduced where the volume to be examined is made from two or more different materials. Modelling work is currently addressing such inhomogeneous media [9], and could provide useful results in the next years.

Obviously, a rather broad gap remains between theory and practice. It may be noted, for example, that transfering an inspection procedure between presumably similar materials cannot yet reasonably be done, as with carbon steel, without experimental verification. Hence, there is generally no alternative to empirical experimentation, which evidently implies that access to the part to be tested or to a representative sample is requested.

3 EXAMINATION TECHNIQUE

3.1 Basic parameters

Whichever the UT-technique eventually selected for a given application, correct wave propagation must be assured through an adequate choice of parameters such as the pulse mode and frequency, or the insonifying beam orientation(s). The prevailing solutions are now very well known and recognized [10,11], and so are as well the concomitant adverse effects as to the inspection sensitivity. The key point thus lies in the compromise to be reached between the antagonist requirements related to the pulse propagation and to its interaction with a reflector.

Two straightforward and essential consequences follow :
- the optimal compromise can be determined only if a sample thoroughly representative of the component to be inspected and of the flaws to be evaluated, is available ;
- restricting the inspection scope (defect type, depth range,...) to the real concern about the integrity of a structure may lead to a differing, yet safer, compromise.

Obviously, the coarse dendritic or equiaxed grain structures encountered in cast material and welds lead to depart much more from the procedures used on carbon steel, than the relatively fine grain of forged material. Therefore, the rest of the paper will address mainly the former case.

3.2 Acoustic beam generation

The previous considerations allow to outline some specific features that a technique intended for flaw detection in austenitic steel testing should ideally offer. First of all, the technique should be easily adaptable to any set of frequency, bulk wave mode and refracted angle, resulting potentially from the compromise between acoustic propagation and sensitivity.

Furthermore, testing methods based on principles requesting a wide dynamic range appear not very suitable for coarse-grained materials, since the scattering noise will generally hide, or at least distort, small signals. Against the common trend, this speaks for a classical amplitude-based approach. To keep then an acceptable sensitivity on small reflectors, one would then normally ask for an equally small beam, what is a priori not compatible with low frequencies, particularly for thick components.

Therefore, all techniques capable of reducing, either physically or virtually, the beam dimension, may be expected to suit well the needs of austenitic steel inspection. In addition, beam shaping does not rule out, if the testing configuration is appropriate, methods such as flaw tip diffraction, pitch/catch disposition, or data processing.

Twin-Crystal Probes

TRL search units are by far the most widely used technique for coarse grain materials. As the apparent beam is produced by the convolution of the sound fields of the separate transmitter and receiver, disposed side by side or in tandem, it is relatively narrow and has a limited depth range. Such transducers provide a noticeable enhancement of the S/N ratio.

Figure 1 displays, as a function of reflector depth, the S/N ratio achieved by several TRL probes on pipe samples centrifugally cast by FAM. The frequency is 2 MHz for the first 20 mm in depth, and 1 MHz for deeper reflectors ; the refracted angle varies from 45 to 90° (creeping wave).

To insonify materials where the scattering is even higher, lower frequencies must be taken into consideration, and the wave propagation improvement is to be balanced, as usually, with the loss of sensitivity resulting from the spreading of the acoustic field and the shortening of the focal distance. Using larger piezoelectric elements compensates for these effects only inasmuch as coupling efficiency can be assured. That physical limit clearly depends on the geometry and surface finish of the part to be inspected.

Focusing Probes

Where a better capability is required, sound beam focusing offers, at the expense of heavier field implementation, high sensitivity and S/N ratio, since even smaller beam dimensions can be obtained [12,13]. Indeed, the degree of focusing can be customized to yield any required beam width (at the focal distance) between the acoustic wavelength and the standard transducer beam dimension. In addition, experience shows that the beam focal characteristics bear up satisfactorily against the disturbances induced by the steel macrostructure. This has been confirmed by numeric simulation using ray-tracing models [14].

Figure 2 compares the results achieved by a TRL search unit and a focused probe on the same reflector machined in a statically cast stainless steel (SCSS) sample : with the same frequency (0.5 mm) and the same refracted angle (45° CW), a S/N ratio improvement of about 6 dB is achieved. Another example of the focusing technique capability is illustrated by figure 3, which shows the echo reflected by a 20 mm deep slot spark-eroded in the back wall of a 200 mm thick SCSS specimen ; a 140 mm diameter emitter refracting compression waves at 30° was used in this case.

4 DATA ACQUISITION AND PROCESSING

The invasion of the NDT world by computers provided access to a large number of digitized signal processing tools. Many of them consist in averaging different A-scans or RF waveforms recorded at successive times or locations ; an alternative technique selects the minimum value from the different samples. Split-spectrum processing also belongs in some way to that family of algorithms, the common feature of which is the elimination of that background noise part which is random among the different samples. In austenitic steel, however, the grain scattering noise is to a great extent coherent, so that the S/N ratio improvement offered by such averaging techniques is generally limited to about 6 dB.

More specific processing techniques have not yet gained the recognition of the industry world, although some of them produced serious prospects of success. Such is the Synthetic Aperture Focusing Technique (SAFT), which can be roughly described as a computerized construction of a virtual focused beam. SAFT has been extensively tested in the laboratory, in combination with probe tandem disposition [15].

Yet the main advantage of stainless steel inspection mechanization and computerization, beyond the evident fallout on reproducibility and reliability, might lie in the ability to acquire and store any signal, down to the backscattered noise level [16]. This leaves a permanent record of the examination, allows subsequent deeper analysis, and facilitates the detection of eventual evolutions, not to mention, for nuclear environments, the reduction of personnel radiation doses.

5 DATA EVALUATION

The economic consequences of misinterpreting geometric and structure echoes as flaws have rightly introduced the false call rate among the criteria used to evaluate the UT-capability on austenitic steel.

From a physical point of view, however, a reflector can be regarded as an acoustic impedance discontinuity. Grain boundaries and weld fusion lines may thus be classified as such, just in the same way as cracks ; it then sounds somewhat simplistic and unrealistic to expect distinct characteristics from those reflector types. This explains the limitations encountered by the time and frequency feature mapping techniques in discriminating between flaws and artefacts.

In the prevailing field practice, interpretation relies still largely on reflector location, in spite of the inaccuracy resulting from the skew and velocity variations induced by the steel macrostructure. Narrow beams, computer graphical displays, multiple examination directions and extensive documentation on the geometry of the examined component are all helpful contributions, but the current capability is not yet fully satisfactory. New directions, among which probabilistic approaches, appear worth investigating, and artificial intelligence may be expected to synthesize in the future the state-of-the-art expertise.

The macrostructure similarly hampers defect sizing. Some benefit can be taken from the means mentioned earlier about location, but the most effective technique turns out to be the conjunction of small beams with flaw tip echoes, where they are detectable, or with amplitude drop methods elsewhere. If obviously the defect sizing accuracy in austenitic material cannot, on average, equal the best performances on carbon steel, flaw evolution can be rather easily detected and, where necessary, custom-designed inspections can often provide excellent results : figure 4 shows an example of B-scan and D-scan image obtained by a focusing transducer from a rectangular plate inserted in the weld fusion line of an inconel nozzle mock-up [17].

6 CONCLUSIVE REMARKS

Austenitic stainless steel inspection procedures must be designed according to a rigorous methodology, addressing all favourable and unfavourable features of the material to be examined, and of the technique and equipment to be implemented.

Ideally, every new case should be primarily considered as singular. It should be investigated on specimens representative of the actual macrostructure(s) and geometry, and containing realistic defects. Needless to say capability assessment must be carried out along the same rules. When field contingencies do not permit to follow step by step such a procedure, the validity of the alternative solutions must be carefully evaluated.

Until now, theoretical developments have most valuably enhanced the understanding of physical phenomena assessed experimentally, but further investigations in modelling work and parametric studies are necessary to produce benchmarks for the practicians.

Using twin-crystal probes or focusing transducers to reduce the acoustic beam width has been found to enhance greatly defect detection and evaluation capability. Reliable discrimination between real flaws and artefacts still relies too heavily on location, and calls for new data processing techniques.

Because austenitic material NDE is never a routine job, the selection of a technique, the design of the equipment and the inspection performance all require highly qualified personnel, well informed on the physics of wave propagation and interaction with reflectors, as well as on the capability of standard and advanced examination methods. Overall field experience is crucial, and specific training can be utterly profitable.

In the past, many tentative implementations of UT on stainless steel may have proven ineffective mainly because the examination procedure design had underestimated the associated difficulty ; such failures should not conceal that valuable results can most often be achieved when the problem is tackled adequately.

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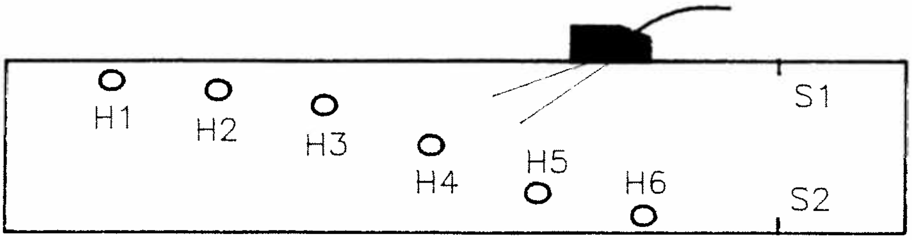

S : spark erosion slot – depth : 1.5 mm

H : side–drilled hole – diameter : 1 mm

(depth : 5, 10, 17, 34, 51, 56 mm)

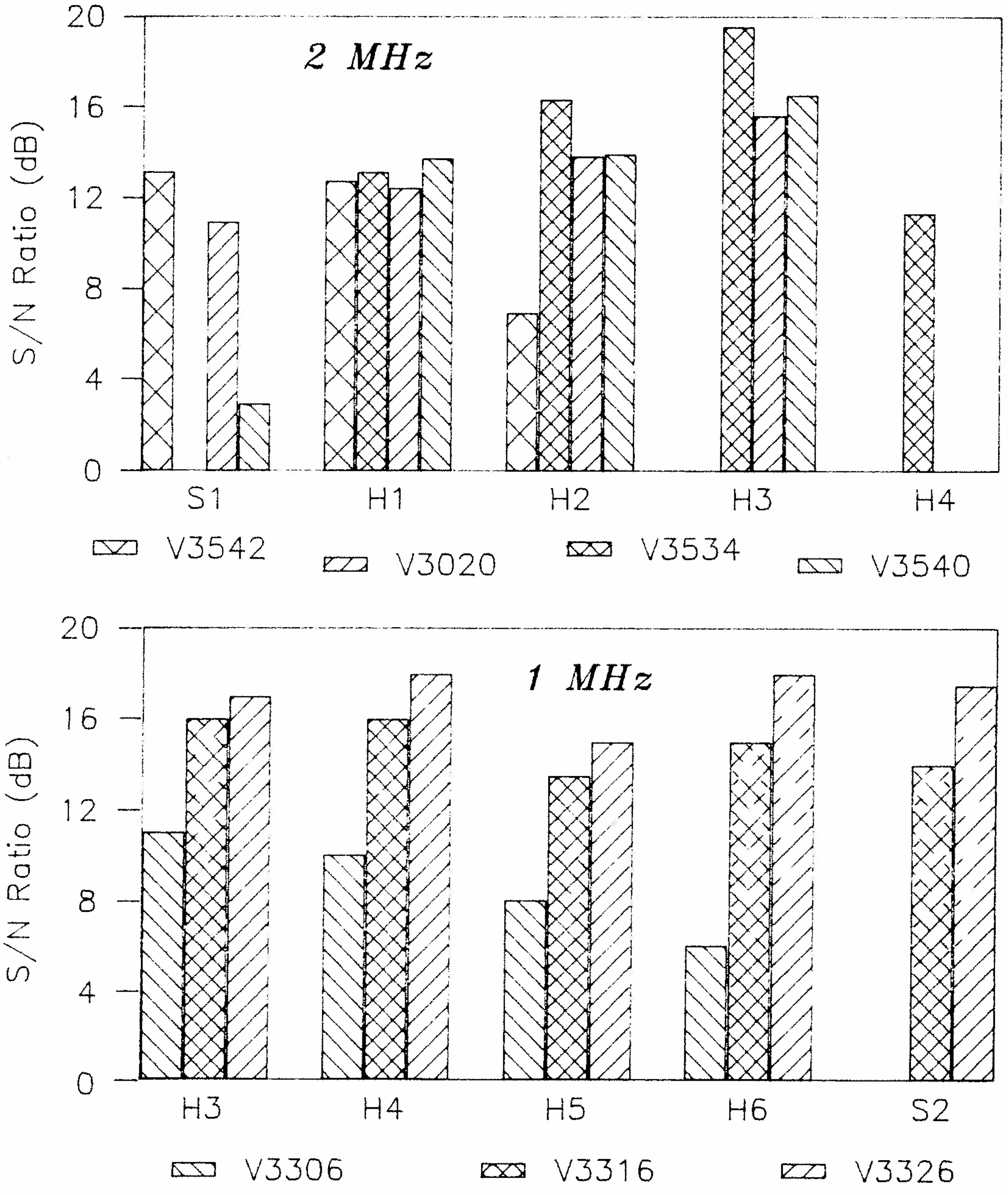

Fig. 1 – Signal/noise ratio achieved on centrifugally cast austenitic steel with TRL transducers

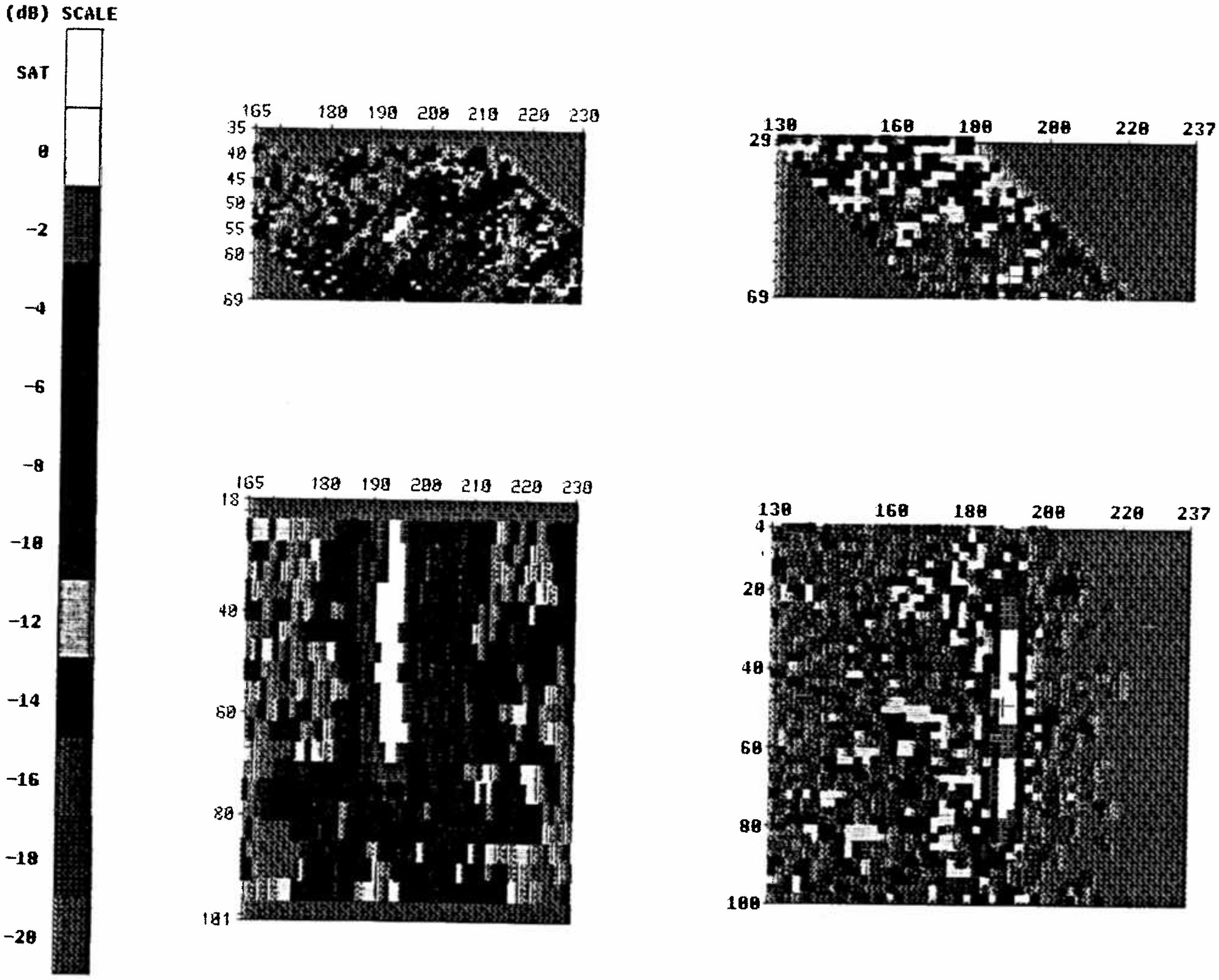

Fig. 2 - B-scan (up) and C-scan (down) views of 4 mm dia. hole side-drilled in SCSS. Left : TRL probe ; Right : focusing probe

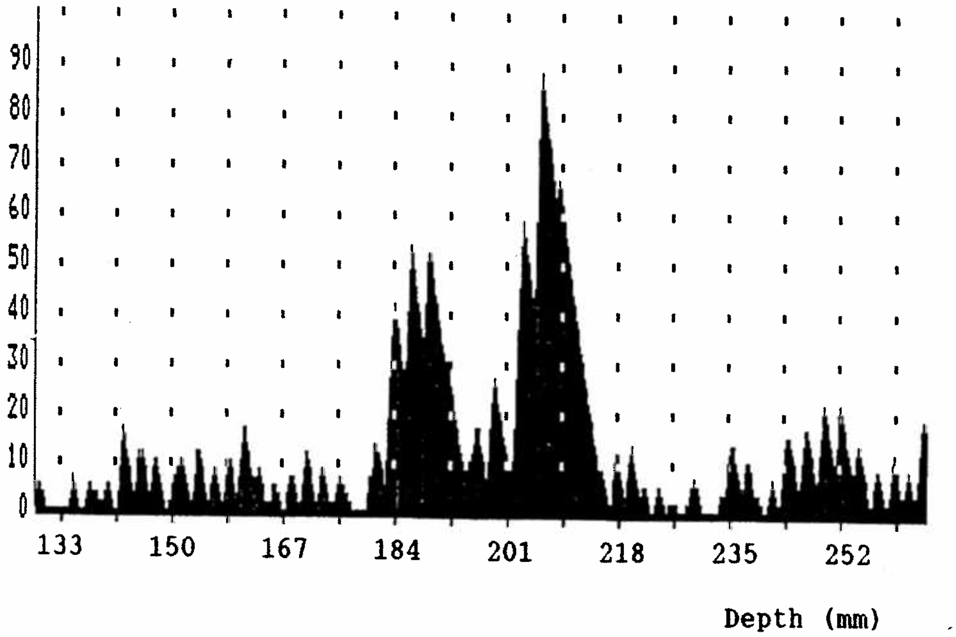

Fig. 3 - Tip echo and corner echo from EDM slot in 200 mm thick SCSS specimen

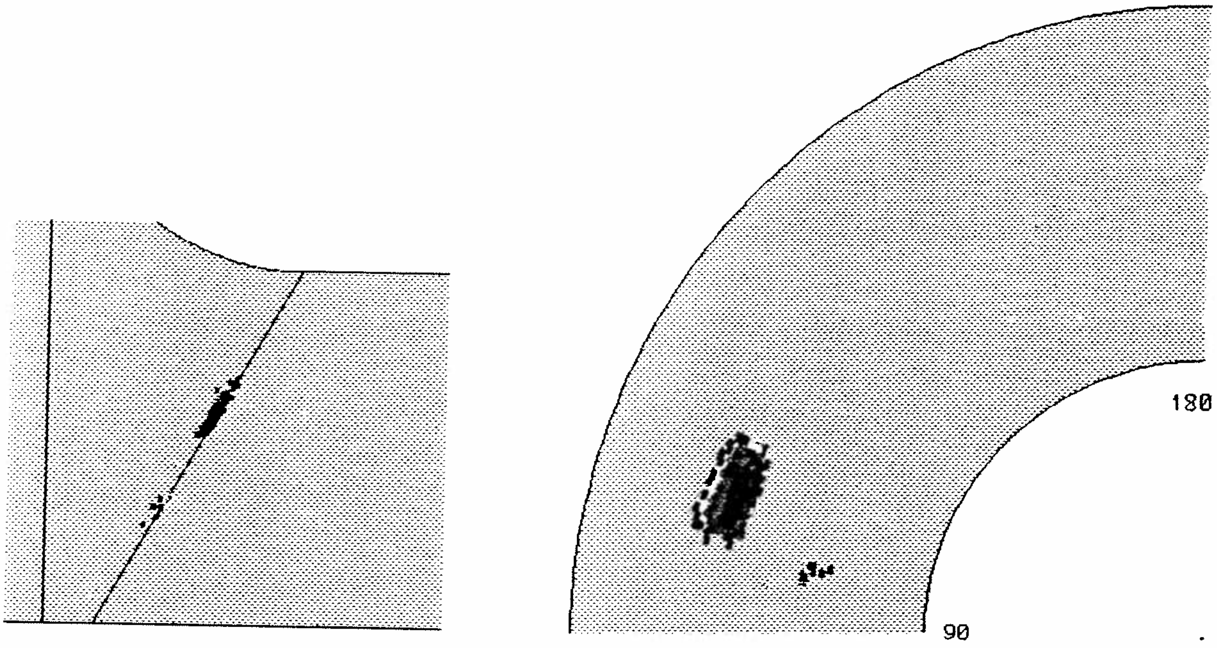

Fig. 4 - Accurate sizing of planar reflector in inconel weld (thickness : 56 mm)