THE ROLE OF NDE IN GLOBAL STRATEGIES FOR MATERIALS SYNTHESIS AND MANUFACTURING

D. O. THOMPSON AND T. A. GRAY
Center for NDE, 303 Wilhelm Hall, Iowa State University, Ames, IA 50010

INTRODUCTION

During the past several years a number of design-centered "global" approaches have been offered that deal both with materials synthesis and with the manufacture of materials into finished products. Although the structure and constituent components of these approaches differ because of their different end purposes, they share major dependencies upon design, theoretical modeling, extensive computations, and confirming measurements using various NDE techniques. Materials-by-Design (MBD) is an example of these approaches that is focused on the synthesis of materials. As noted by Eberhard[1], a principal purpose of Materials-by-Design is to produce materials with prescribed macroscopic material properties by designing and controlling material structures at the atomic and molecular levels. At the other end of the spectrum, Unified Life Cycle Engineering (ULCE)[2] is an example of a "global" model for manufacturing. In this case, emphasis is placed upon the development of ways to predict the total set of important properties of a product--performance, quality, reliability, maintainability, and life cycle costs--at the designer's board. Taken together, these approaches offer the opportunity for designer-controlled materials with specified material properties to be fabricated into components of specified performance, quality, reliability, and cost. Even though this combination represents an idealistic vision which may never be perfectly realized, the potential payoff is so large that even imperfect realization may be worth a significant investment. Efforts in these directions can now be made because of the convergence of theoretical, instrumental, and computational techniques.

It is the purpose of this paper to describe some developing concepts in quantitative NDE and provide some examples of their potential use in the evolution of these global approaches. Due to limitations of space and time, emphasis in this paper will be placed primarily upon the role of NDE in the development of the ULCE concept; the conceptual extension of the role of NDE to Materials-by-Design concepts is straightforward.

UNIFIED LIFE CYCLE ENGINEERING (ULCE) AND PROBABILITY OF DETECTION (POD)

It is useful to refer to Fig. 1 in order to describe the ULCE concept and to examine the role of NDE in it. This figure shows a schematic diagram of a possible model of an integrated manufacturing system that is design centered and that contains the kinds of engineering functions commonly associated with a high-technology manufacturing enterprise. These functions are shown in circles and are connected by various links. The solid link connecting the Design and Forming Operations functions represents current CAD/CAM technology, i.e., the technology that has been developed in recent years that enables the designer to communicate and to interact with material forming operations (e.g. machining, casting, forging, etc.). The dotted lines indicate analogous, but

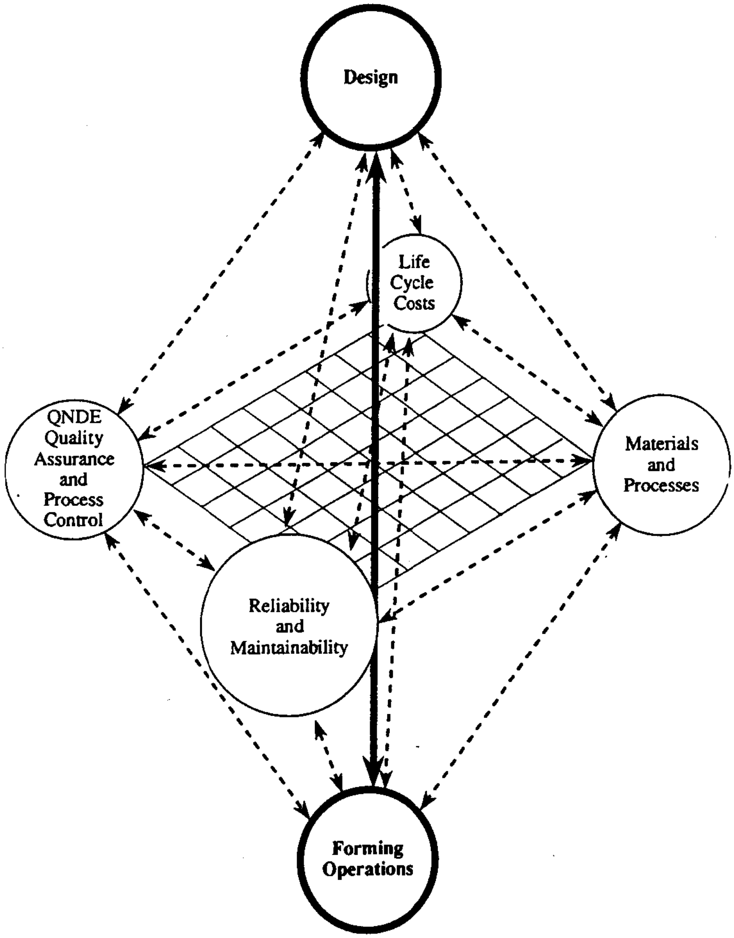


Fig. 1 Schematic representation of possible linkages needed for Unified Life Cycle Engineering (ULCE).

as yet, non-existent links that would permit the designer to interact equally well during preparation of the design with other engineering functions of the manufacturing operations, i.e., functions such as those listed in the other circles. These functions, which have a support character, are necessary in order to realize the ULCE goals. Activation of all these links would permit the designer to be interactively and simultaneously coupled with all the engineering functions in a way that is comparable to the current CAD/CAM link. Successful development and operation of this network would then allow the designer to incorporate all trade-off considerations at the time of product design, would reduce the need for design retrofitting, and would undoubtedly increase the efficiency of the manufacturing process remarkably. Successful development of the ULCE concept could provide a new paradigm in manufacturing.

PROBABILITY OF DETECTION (POD)

With the above model of a ULCE factory in mind, it is necessary to examine approaches that are available to develop the linkages shown in Fig. 1. In this paper, only the QNDE/Design linkage will be considered. Clearly, the approach needed to develop and implement this coupling is vastly different and more advanced than any encountered in current NDE practice. For example, the QNDE/Design link needs to provide the designer with several pieces of quantitative information related to the design. These include:

1. A figure-of-merit that can be calculated at each spatial point of a design that quantifies its inspectability for "critical" flaws (or values of material properties) and for various QNDE measurement techniques.

2. Feedback information that will guide the designer in altering design characteristics (e.g. shape, size, material, etc.) as needed in order to improve inspectability while simultaneously meeting other design constraints.

3. Ways to calculate a component scan plan for automated production inspections that will assure the realization of calculated design inspectabilities.

A logical approach for the development of the QNDE/Design link is based upon the probability of detection (POD) concept. This concept possesses the necessary features to fulfill the above requirements. By way of background, it is a broadly used NDE measure which measures the probability that a specified flaw will be found in a given sample using a specific inspection technique. Figure 2 shows an idealized POD curve in which the probability of a flaw's detection is shown plotted as a function of flaw size for both a real and an ideal inspection technique. For the ideal technique the POD of flaws smaller than a critical size is zero whereas the POD of any flaw greater than a critical size is unity. In this case there are neither false rejects (FR) of good parts nor false accepts (FA) of defective ones. However, real NDE techniques are seldom, if ever, as sharp and as discriminatory as that indicated by the ideal curve, with the result that there are regions of uncertainty shown by the false reject and false accept areas. Without going into detail, it is evident that various features related to these uncertain regions that are essentially defined by the quality of the QNDE inspection technology include information that can be utilized in the development of other linkages shown in Fig. 1.

To date essentially all applications of the above-described POD concept have been empirical, i.e., a statistically significant number of samples is prepared with artificial flaws, and then experiments are made by various operators utilizing specific NDE techniques. POD, or confidence level, results are then derived from these data. It is evident that such empirically derived results represent insufficient bases for the development of the QNDE/Designer linkage of Fig. 1, even if coupled with expert systems or other artificial intelligence approaches. First, the empirically determined POD curves represent a "convolution" of operator and instrumental capabilities. It is not possible to isolate these two sets of variables on the basis of empirical results only; hence, the degree to which any empirically determined POD curve represents the true POD determined by physical principles only (part shape, materials, details of measurement system, etc) is unknown. Secondly, empirically determined POD's cannot be used, with confidence, to predict POD values for other sets of measurement conditions. For example, there is no way to predict a POD at a given location in a part from an empirically determined POD measured at a different location with different part geometries. Without this predictive property, the utilization of POD during the evaluation of a design is impossible without readily available, extensive empirical histories of previous cases

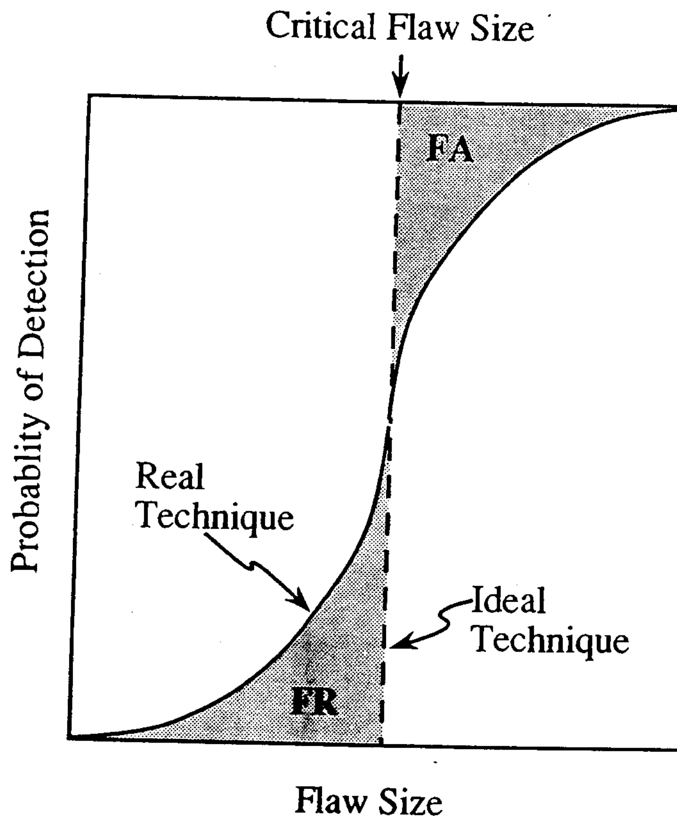


Fig. 2 Probability of detection (POD) curve as function of flaw size for both ideal and real NDE techniques.

perhaps combined in an appropriate expert system. Even if this were possible technically, it would more than likely be economically prohibitive to develop such an inventory.

THEORETICAL MODELS OF POD AND APPLICATION TO DESIGN DECISIONS

In recent years, early versions of theoretical models that permit calculations of POD's to be made have appeared for three major QNDE technologies--ultrasonics[3], eddy currents[4,5], and microfocus radiography[6]. In contrast to empirically determined POD's, these are first principle engineering models that can be used as a basis for the QNDE/Designer linkage shown in Fig. 1. Without going into detail here, these first principle models are analytical models of the QNDE measurement process and depend upon details of the measurement setup for each inspection technology. For example, the details include the geometry of the component being inspected, relative inspection configuration of probe and part, characterization of the generation, propagation, and reception of the interrogating energy (e.g. in the ultrasonic case, this characterization depends upon knowledge of the transducer radiation pattern, refraction of the beam at the part's surface, beam propagation characteristics in the host material including material anisotropy, attenuation, diffraction losses, etc.), critical flaw information that is obtainable from materials engineering, detailed models of field-flaw interactions from which flaw responses can be calculated for a known interrogating field, and finally a knowledge of noise conditions that adds uncertainty to the measurement results. Thus, the first-principle engineering POD models require the kind of fundamental results, e.g. ultrasonic scattering models, that have been obtained in various QNDE research efforts over the past 10-12 years.

Figure 3 shows an example of a POD calculation for μ-focus radiography using a film detector and for three different accelerating voltages in which the expected POD curve shape is realized[6]. In this case, the POD model consists of five parts that describe the generation of the x-ray beam from specific machine geometries, the energy-dependent interactions of the beam with the sample, the experimental configuration, details of the detector, and a description of the detectability criteria. They are based on eqns. (1) and (2), i.e.

$$I(x,y,E) = I_o(E)\int_{source} \frac{e^{-\mu(x,y,E)\cdot\rho}\,dA}{r^2(x,y)} \quad (1)$$

$$D(E) = D_o(1 - e^{-\sigma[(1+\eta)I(E)t+\delta]}) \quad (2)$$

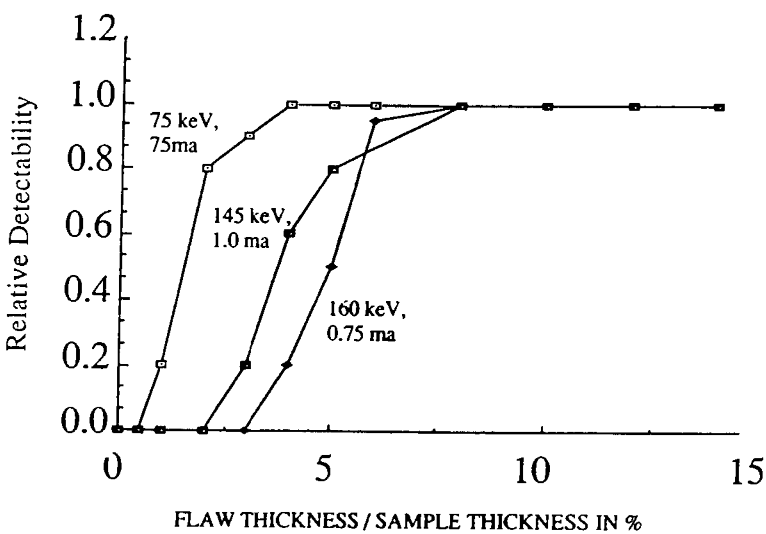


Fig. 3 Theoretical POD curve for μ-focus radiography.

in which I is the intensity immediately above the detector, I_0 is the initial intensity produced by the x-ray generator, μ is the energy dependent linear absorption coefficient, ρ is the x-ray path length through the sample, r is the distance from the source to the detector, and x, y are the coordinates at the detector surface. In eqn (2), D is the film density, σ is the interaction cross section of an x-ray with a film grain, η is the coefficient of the x-ray scattering, δ is the natural film fog density, and D_0 is the maximum film density. As can be seen, the sensitivity drops as the hardness of the beam increases, a well known result.

POD modeling for ultrasonics is somewhat more advanced than the previously described x-ray case. Limited applications can now be shown for simple cases that demonstrate the way in which the models can be used to develop the QNDE/Designer link and which show that the quantitative information required by a designer can be obtained. Figure 4 shows a case in which a POD calculation

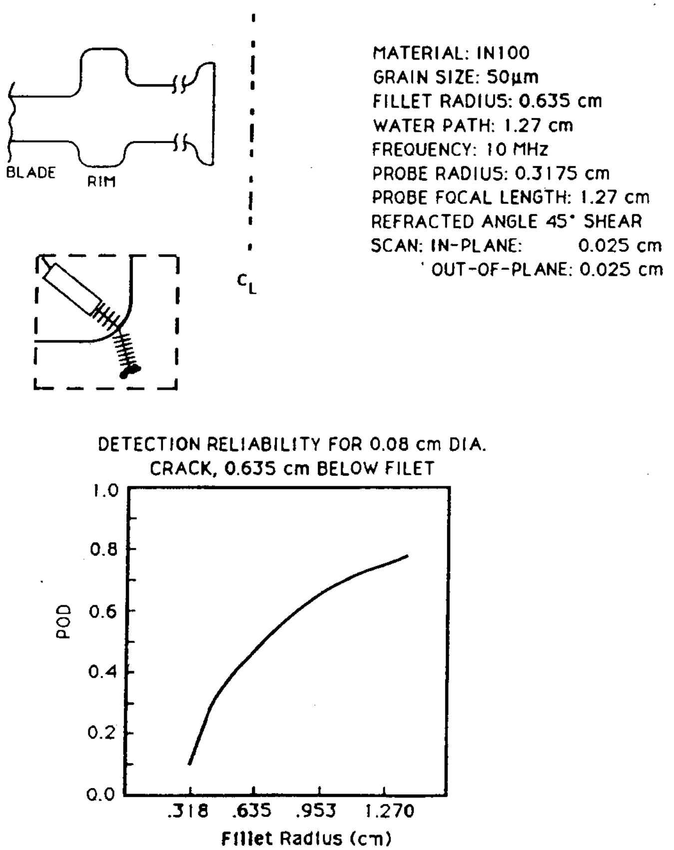


Fig. 4 Suggested design improvement using POD model for ultrasonics.

has been combined with a critical flaw specification to show how a design could be improved to enhance inspectability[3]. In this case, the component is a turbine engine blade as shown in the upper left hand corner of the diagram, and immediately below it, the particular area of interest (the fillet region of the blade including the location of a critical flaw) is shown in a magnified form. The inspection geometry is implied in this magnified section, and details of the ultrasonics and blade materials are given in the upper right. Results of POD calculations for this inspection geometry, material, and critical flaw are given in the lower part of the figure as a function of the fillet radius. It can be seen that, for the postulated inspection capabilities, the POD is less than 0.5 at the design fillet radius of 0.635 mm, but that it improves as the fillet radius is increased. The designer could obviously use this information to select a final fillet radius that would be both inspectable and compatible with other requirements. Most importantly, this information is available at the design stage before any final commitments of the design are made and before any added-value is accrued. Such information also provides a research guide for improved inspection capabilities. Design options could be extended with new variations in the inspection methodologies.

Figure 5 demonstrates another important capability of the POD model that can be used by the designer. In this case, the model is used to pre-determine the parameters of an automated scan plan that can be used to assure the designed-in inspectability[3]. An assumed circular part shape with a complex cross section is shown in the upper left hand corner together with the material and ultrasonic specifications shown in the upper right. The bottom part of the figure shows POD calculations as a function of flaw (crack) radius placed at 3 different depths in the part (cf code at bottom of figure). It is seen that scan plan #1 with its set of scan parameters produces a widely divergent set of POD results for the 3 different flaw depths whereas scan plan #2 with its selected scan parameters produces a uniform POD pattern for the same 3 different flaw depths. The designer could thus extract information from these calculations that can be used as inspection specifications for automated inspections.

Figures 6-10 show a sequence of preliminary results in which the ultrasonic POD models for both inspectability and optimal scan plan have been combined with other tools of the designer[7] to produce a design that is optimized for inspectability and thereby reliability. Figure 6 shows a perspective view of an axially symmetric component, a disk, that was produced using a wireframe and solid model design technique. As indicated in the figure, the fillet region is a region of particular interest for inspectability. Figure 7 shows schematically the next step in the analysis that brings in materials, fracture mechanics, and performance information. In this step, a finite element mesh is incorporated into the initial design, and stress analyses consistent with design performance profiles are then made. From this information together with known material properties, critical flaw information is developed. Critical flaws are then placed upon the mesh nodal points, and POD values are then calculated at the nodal points for the critical flaws assuming specific ultrasonic inspection parameters. The results of the POD calculations for two different fillet radius design values and scan inspection parameters are shown in Figs. 8-10. Values of the POD in these figures range from 0 to 1, the lightest end of the grey scale being 0 and the darkest end corresponding to a unity POD. Legends in the figures give the appropriate parametric values. The scan mesh (Δx) is a scan parameter and is measured radially along the disk diameter, and r is the fillet radius. It is assumed in these calculations that the axis of the inspecting transducer remains normal to the fillet surface while inspecting through the fillet region. It is evident, as shown in Fig. 10, that significant improvements in inspectability, and hence component

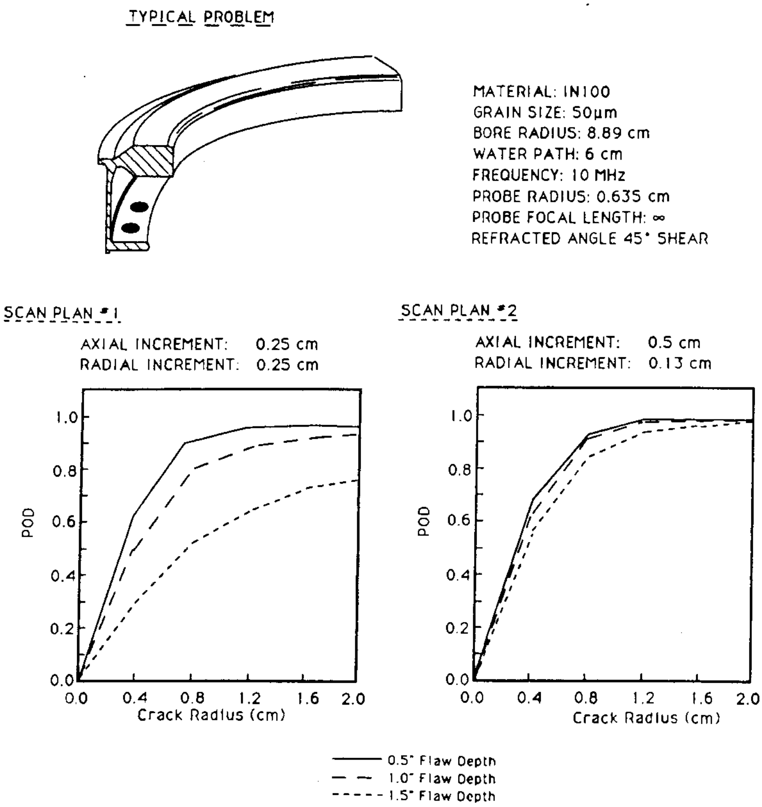


Fig. 5 Application of POD model to specification of automated inspection plan.

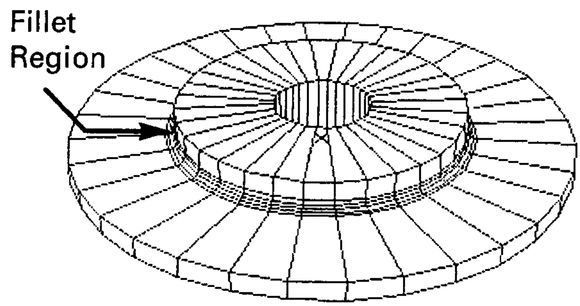
reliability, can be made at the design level while requiring only fairly insignificant changes in the design itself and in the specification of inspection routines.

SUMMARY

The development and utilization of computationally intensive "global" models to predict the properties of materials and manufactured products would appear to offer new paradigms in materials and product designs. In the first case, materials would be designed on the atomic level to produce desirable macroscopic properties, while in the second, products would be interactively and quantitatively designed for performance quality, reliability, maintainability, and estimates of life cycle costs. The realization of these new paradigms requires substantial new tools in QNDE measurements that can be applied both to material property and flaw measurements. One of the most promising approaches to provide the designer with key quantitative information in the manufacturing and processing case is the theoretical POD models that are becoming available for various NDE techniques. These models are no more and no less than quantitative physical models of the measurement process evaluated for specific design problems. When utilized and combined with other tools available to a designer, they form a key link in the development of the ULCE concept.

Wireframe Design Model of Disk

- Solid Model contains geometric and material properties of component



Perspective View

Fig. 6 Perspective of disk generated using wireframe and solid model techniques.

Finite Element Model

- Nodes provide points in object at which POD can be calculated

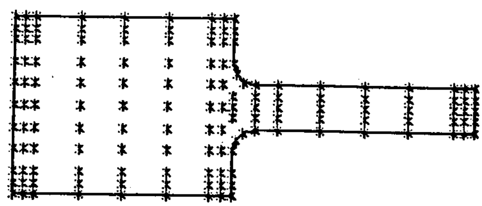


Fig. 7 Specification of finite element mesh in cross section of disk (cf. Fig. 6)

POD Contours - "Nominal" Scan & Design Parameters

- Course scan mesh (Δx = 0.25 cm)
- Tight fillet radius (r = 0.50 cm)

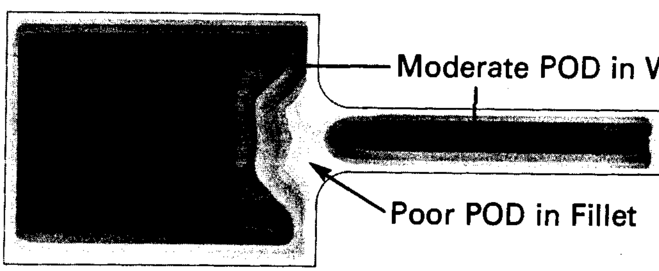


Fig. 8 Cross-section of disk showing POD contours for "Nominal" Scan and Design Parameters for a specific set of ultrasonic tools. Note poor POD in fillet region

POD Contours - "Optimal" Scan, "Nominal" Design

- Fine scan mesh ($\Delta x = 0.10$ cm)
- Tight fillet radius ($r = 0.50$ cm)

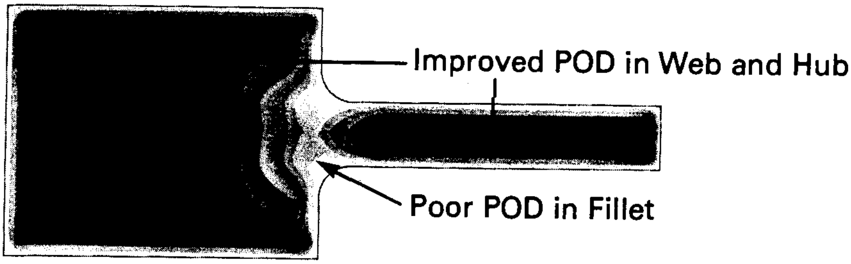


Fig. 9 Cross-section of disk showing improved ultrasonic POD contours that result from a scan mesh that is smaller than that used in Fig. 8.

POD Contours - "Optimal" Scan & Design Parameters

- Fine scan mesh ($\Delta x = 0.10$ cm)
- Moderate fillet radius ($r = 1.0$ cm)

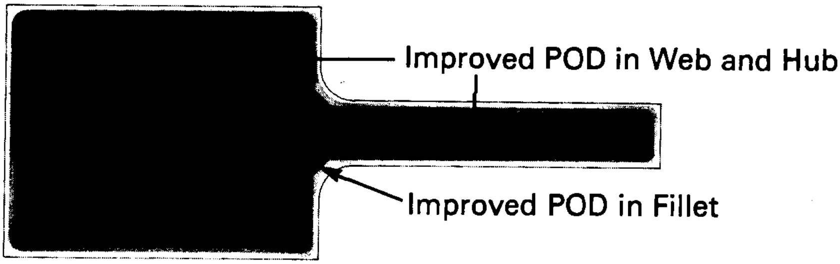


Fig. 10 Cross-section of disk showing nearly uniform ultrasonic POD contours that result from the smaller scan mesh (cf. Fig. 9) and an increased fillet radius (cf. Figs. 8 and 9).

REFERENCES

1. J. J. Eberhard, "Materials-by-Design," ECUT Program Bulletin, June, 1988, USDOE.

2. H. Burte and D. Chimenti, "Unified Life Cycle Engineering: An Emerging Design Concept," in Review of Progress in Quantitative Nondestructive Evaluation 6, D. O. Thompson and D. E. Chimenti, eds., (Plenum Press, New York, 1987), p 1797-1809.

3. T. A. Gray and R. B. Thompson, "Use of Models to Predict Ultrasonic NDE Reliability," in Review of Progress in QNDE 5, D. O. Thompson and D. E. Chimenti, eds., (Plenum Press, New York, 1986), p 911-918.

4. A. J. Bahr and D. W. Cooley, "Analysis and Design of Eddy Current Measurement Systems," in Review of Progress in QNDE 2, D. O. Thompson and D. E. chimenti, eds., (Plenum Press, New York, 1983), p 225-244.

5. R. E. Beissner, K. A. Bartels, and J. L. Fisher, "Prediction of the Probability of Eddy Current Flaw Detection," in Review of Progress in QNDE 7, D. O. Thompson and D. E. Chimenti, eds., (Plenum Press, New York, 1988), p 1753-1760.

6. J. N. Gray and F. Inanc, "Three Dimensional Modeling of Projection X-Ray Radiography," in Review of Progress in QNDE 8, D. O. Thompson and D. E. Chimenti, eds., (Plenum Press, New York, in press).

7. CAD Simulations were performed using I-DEAS from Structural Dynamics Research Corp.