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Roller Burnishing – A Cold Working Tool to Reduce Weld Induced Residual Stress

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Abstract

The possibility of stress corrosion cracking (SCC) in regions of tensile residual stress introduced by weld deposited material has been a concern where environmental effects can reduce component life. Roller burnishing, a form of mechanical cold-working, has been considered as a means of providing for residual stress state improvements. This paper provides a computational evaluation of the roller burnishing process to address the permanent deformation needed to introduce a desirable residual stress state. The analysis uses a series of incrementally applied pressure loadings and finite element methodology to simulate the behavior of a roller burnishing tool. Various magnitudes of applied pressure loadings coupled with different size plates and boundary conditions are examined to assess the degree and depth of the residual compressive stress state after cold working. Both kinematic and isotropic hardening laws are evaluated.

Introduction

Roller burnishing is a cold-working process that has demonstrated applications in the material processing and manufacturing arenas. One such application is the joining of tubes to tubesheets for heat exchanger applications. This joining is achieved by expanding a tube into the tubesheet through this cold-working mechanical process. The residual stress generated by the tube/tubesheet expansion creates a bond (interference fit) between the two parts. An example of this particular application and the associated finite element analysis is reported in References [a] & [b]. Reference [c] discusses roller burnishing as a tool for smoothing/finishing a component surface after grinding and depicts final surface qualities as the basis for process parameter acceptance. In addition, Reference [c] reports a transformation of tensile residual surface stresses into compressive residual surface stresses through means of roller burnishing. Reference [d] applied similar processing techniques as a means of expanding fastener holes in aluminum plates to introduce compressive residual stress for improved fatigue performance. References [e] & [f] focus primarily on the roller burnishing process as a means of improving surface hardness and microstructure in aluminum.

Discussion

This paper discusses the application of roller burnishing as a potential tool for relief of tensile residual stresses in penetrations and nozzles generated by a weld deposited cladding overlay on a base material. The concept is to introduce sufficient deformation into the weld deposited surface such that the subsequent residual stress state will be compressive. A test program was developed to combine the concepts of the aforementioned applications into a stress relief improvement package for regions with weld-deposited cladding. This test program was initiated to (a) obtain first hand experience with the roller burnishing process, (b) develop processing parameters and evaluation of methodology, and (c) confirm the process results in compressive residual stress. The computational work described in this paper helps develop the parameters needed to fulfill the test program objectives. A computational evaluation is performed to quantify loading requirements and support qualification of the process for field applications. A finite element analysis simulates the behavior of the rolling tool through a series of incremental loads applied around the inner bore circumference of a simulated penetration.

This paper reports the analysis models, assumptions, loadings, and results in support of proof-of-principle mock-up testing. The main objective of this paper is to define the mock-up support. This mock-up support is defined to include (1) determination of the mock-up outer diameter necessary to adequately represent prototypical constraint conditions; and (2) prediction of the amount of bore expansion necessary to create a residual compressive stress state at the inner surface. To facilitate field measurements, a minimum of 0.003 inches permanent deformation is needed with an arbitrarily desired compressive stress field depth of approximately 0.010". As an initial estimate of the mock-up size, a 7 inch outer diameter with a 1.75" inner diameter is chosen.

The roller burnishing tool used for this application consists of three equidistant rollers. Each individual roller has an outer diameter of 0.465" with 0.100" of contact area for an inner bore diameter of 1.75". Each roller rotates about its local axis while also rotating around the inner bore diameter at a uniform controlled speed. These rollers have the capability to increase the load/depth of penetration applied to the inner penetration surface while rotating about the bore. Initially high strength rollers compress the surface elastically until the material yields. Further increase in loading subjects the surface to plastic deformations (work-hardening with increased strain). Upon unloading, there will be a small amount of elastic recovery, but the overall bore diameter will increase. The amount of permanent deformation after unloading is compared with the magnitude and depth of the residual compressive stress state to facilitate development of the appropriate test procedure.

Assumptions

As with any finite element model simulation some simplifying assumptions are made to facilitate the analysis. For this particular evaluation the following assumptions are made:

1) A frictionless interface is assumed between the rollers and the inner bore based on the application of lubrication during the rolling process.
2) The finite element model assumes a plane strain condition based on the desire for a uniform final deformation along the entire inner bore surface.
3) Although the rollers apply load in a continuous manner, the analysis is considered a static analysis as opposed to a dynamic analysis. This assumption is based on the relative rolling speed of the cylinder being slow (0.088ft/sec) compared with a surface wave propagation speed, υ_{cr} (steel = 9,900 ft/sec).

4) The arc of contact is considered to be circular and the contact zone small.

5) Plane sections perpendicular to the direction of the rolling remain plane and small scale yielding is considered. This is consistent with results reporting small deformations.

6) The analysis assumes room temperature (70F) as a reference temperature. No allowance is taken for the increase in temperature that will occur as a result of the cold working process.

Finite Element Model

The finite element model is developed to accommodate mock-up plate outer diameters of 7.0", and 9.0" (see Figure 1). The weld deposited zone on the inner diameter is 0.400 inches deep. In addition, the actual mock-up plate is 2" thick. The applicability of the plane strain assumption is based on the rollers applying a load over a small portion of the thru-thickness over each pass. The unloaded surrounding material in the Z-axis direction provides sufficient restraint at all cross-sections removed from the end surfaces.

A finite element mesh is created to facilitate simulation of roller contact. The calculated roller contact area (0.100") is based on the formula in Appendix A. Using a bore diameter of 1.75 inches and a total initial contact surface area of the bore circumference (5.4977 inches) a total contact area per revolution is established. Given the use of three rollers in this burnishing process, the total contact length is subdivided into three separate lengths. Using these dimensions and an arbitrarily set depth (0.100") of a compressive stress field, a mesh refinement is designed to cover the first 0.100 inches of weld deposited material. Element aspect ratio as close to one-to-one is retained. Subsequent mesh patterns are dictated by the initial mesh refinement but are also developed with computer resources in mind (see Figures 2 through 4).

Boundary Conditions

Two independent sets of boundary conditions are examined. One represented the actual mock-up conditions where the plates are fixed at three (3) equidistant locations around the outer plate circumference at the mid-plane location. This boundary condition is simulated by fixing the finite element model at three equidistant nodes within the in-plane axis. The nodes selected for the placement of these fixed boundary conditions coincide with a line emanating radially outward from the starting point of each roller. This boundary condition permits the majority of the outer surface to displace under the applied loading. This boundary condition represents the mock-up condition.

The second applied boundary condition represents a fixed surface boundary condition and is simulated by restraining the entire outer circumferential diameter against any radial deformation due to the applied loading. This boundary condition represents a penetration through an infinitely wide thick shell. This boundary condition provides an upper bound on outer surface restraints.

Using the same magnitude loading for each displacement boundary condition forms the basis for determining (1) the minimum required mock-up plate outer diameter and (2) the effects of roller burnishing and the displacement boundary condition assumption on the residual stress state.

Applied Loading

Initially a single magnitude rolling pressure loading is applied normally and radially outward along the inner circumference. In an effort to develop a permanent deformation of 0.002 to 0.003 inches after unloading, various pressure loadings are examined ranging from 75 ksi to 200 ksi. The method of load application for the available finite element software package consists of uniform elemental pressure loadings applied to constant strain elements. Contact surface type loading capabilities are not available in this software package.

The simulation of the actual burnishing process requires a large number of successive loadings and unloadings to occur in rapid succession around the inner circumference. This is impractical without the use of moving rigid contact surfaces. Thus, an elemental pressure loading is applied and removed in a limited prescribed sequence using history tables that simulate the roller movements around the inner circumference. The loading pattern over a series of elements representing roller contact is accomplished by defining a ramp up in pressure, a hold period at a specified pressure, then a gradual ramp down of the pressure loading for each inner surface element. This loading sequence engages multiple elements simultaneously as shown in Figure 4.

Subsequent load cases are run with the magnitude of pressure increasing incrementally with each subsequent revolution as directed by history table manipulation. For the multiple pass cases, the loading pattern is similar to that of the single pass case, only each element experiences more than one loading/unloading prior to attaining a final deformed geometry of 0.002 – 0.003 inches at the inner bore diameter. Each successive pass increases the applied load by 25 ksi starting at 150 ksi. This increase in magnitude coincides with the increase in depth that occurs with each revolution of the roller about the bore circumference. This method of loading is more prototypical of the actual roller burnishing process.

Material Properties

The material properties used in this model consist of two different base metals and one type of weld deposited cladding. For both cases the weld deposited material consists of ASME A308L. The actual mock-ups in the test program used two different base metal materials (ASME A304 or A508 Class 2) to assess the effects the backing material has on the ability to develop compressive residual stresses in the inner bore surface.

Initially the analysis was performed with isotropic hardening, but due to the magnitude and reversal of the stresses during the unloadings, it was subsequently determined that kinematic hardening is more appropriate for this application. Hence additional cases are run with the kinematic hardening material model.

Trends and Results

This section reports on the results of the finite element analyses as a series of comparative studies directed at determining the feasibility of roller burnishing for developing compressive residual stresses on the inner bore surface. The various parameters evaluated are summarized in Table 1. These studies address: (1) the minimum outer mock-up diameter that will not affect the inner bore residual stress; (2) the impact of the assumed outer surface boundary conditions on the inner bore residual stress; and (3) the loading (magnitude and type-single or multiple) necessary to attain the desired compressive residual stress state and deformation around the inner surface. In addition to the total amount of deformation, the effective stress is used as the basis for comparison between cases, while the maximum principal stress is used to confirm the regions of compressive stress.

Minimum Mock-up Diameter

The 7" and 9" outer diameter plates were compared using a single pass loading of 125 ksi applied pressure using isotropic hardening, ASME A304 base metal, and the mock-up condition. The corresponding results were almost the same. The 9" diameter plate reported 0.00172" of permanent deformation whereas the 7" plate reported 0.00174" of permanent deformation. For these cases the stress magnitudes differed by < 1% and deformation patterns were nearly identical. The only difference was a slightly higher tensile stress for the 7" plate in the region outside the weld deposited clad. For the locations where loading was initiated, the deformation resulted in a localized peaking. For the locations representing termination of the loading sequence, a slightly lower localized final deformation was observed (Figure 5). These observations are judged to be a function of the potential hardening of the material in the vicinity of the initial loading and the suddenness of the applied loading/unloading. This material hardening due to the loading and unloading may not deform as much under the constant loading applied for this case. With an increased material strength, the same applied load will not generate the same amount of deformation as for a "softer" material.

Boundary Condition Study

Two different boundary conditions were evaluated as a means of bounding the effects of the mockup plate dimensions on their ability to attain a residual compressive stress state at the inner surface. The two boundary conditions represent a fixed outer diameter and a three point fixed condition (mock-up condition). St. Venant's principle is used as the basis for acceptability of the boundary conditions. The stresses or strains created by localized loadings are expected to decrease with increased distance from the loading.

This comparison relies on the models used in the first study, a single pass loading for both the 7 " and 9" plates. However, each plate was run with both the fixed and mock-up outer diameter boundary conditions. The final deformation observed at the inner surface is taken as the basis of comparison. There is very little difference (< 0.0001 inch) reported between each of the plates within a selected boundary condition. However, there is a slight decrease (0.0030") in the overall permanent deformation that occurs around the inner surface for the fixed boundary condition as compared with the mock-up boundary condition. This decrease in deformation is attributed to the stiffer structure generated by the fixed condition and the application of a constant load.

In addition to examination of the displacements, very little difference is observed in the trends and stress patterns for either boundary condition. This observation held for the maximum principal stress and the effective stress patterns and magnitudes in both plates. The minimal principal stress differences support the use of the 7" diameter plate for the mock-up testing. An example of the three point support for the multipass 7" diameter plate is shown in Figure 6. In this figure the uniformity of the stress at the bore surface reflects the lack of impact on the results by the support locations.

Deformation with respect to Applied Loading

Having established the adequacy of the 7" mock-up plate with respect to diameter and boundary conditions, the model was evaluated for the magnitude of the load necessary to obtain a minimum of 0.003 inches permanent deformation after unloading. The results of this phase of the study determines the feasibility of roller burnishing to develop compressive residual stresses and to what depth they exist. A series of single pass pressure loadings on the circumference of the bore are undertaken with loadings varying from 100 ksi to 200 ksi in increments of 25 ksi. The results of these single pass cases indicate that the entire inner surface does not reach a permanent deformation of 0.003 inches until a load of 175 ksi is applied. At an applied loading of 200 ksi the minimum residual deformation is 0.0054 inches. However, at the locations of the initial applied loading the residual deformation reached 0.027 inches. This high localized deformation is a result of a single loading and is not representative of the actual roller burnishing process, which is a multipass, incrementally increasing loading.

Multipass Loadings

To provide a closer simulation of the roller burnishing process, a three pass applied loading case was evaluated. Each pass incrementally increased the magnitude of the applied load. The results of the multipass case are compared with those from the single pass 200 ksi loading case. Comparison of the maximum principal stress and effective stresses and displacements between the two cases show that the single pass case has significantly higher magnitudes for all three measures. For the single pass case, the displacements are 2.5x greater, the maximum principal stress is 1.5x greater, and the effective stress is 1.25x greater.

These diverse results are attributed to the different methods of applied loadings. The single pass model provides a sharp loading and unloading pattern which results in distinct pockets of sharp stress gradients. The multipass load case obtains the results by a gradual ramping up to the final applied load. This cyclic loading/unloading affects the final magnitude of the residual stress and deformation. There is also a smoothing of the plastic stress redistribution in the multipass case.

Figure 6 plots the maximum principal stress for the 7" diameter plate case with three fixed points, multipass loadings, and with isotropic hardening. Figure 7 shows the maximum principal stress for the 7" diameter plate case with multipass loadings, fixed outer boundary, and a kinematic hardening material model. The isotropic material model results in pockets of tensile stress within the clad layer, while the kinematic hardening material model results in a continuous compressive stress state through the depth of the clad. The use of the kinematic hardening material model results in more deformation occurring for an equivalent magnitude of applied loading when compared with an isotropic material hardening model. The kinematic hardening material model is judged to represent a closer approximation to the actual roller burnishing application.

Effect of Base Material on Results

Using an initial condition of a 7" diameter plate, mock-up outer boundary condition, and a single pass applied loading, two cases with different base materials (A304L and A508) were considered. The results of these analyses showed very little difference in the magnitudes of the displacements or principal stresses between the two cases. Although there are slightly higher compressive stresses and permanent deformation at the inner surface for the A304L base material, the compressive zone extends all the way to the base material for the case with the A508 base material. This increase in compressive residual stress depth is attributed to the slightly stiffer backing afforded to the cladding by the A508 material.

Uncertainties

With any finite element analysis there are uncertainties associated with the initial assumptions made to facilitate performance of the analysis. Two uncertainties associated with the preceding work are discussed and are not judged to significantly affect the results presented or the conclusions drawn.

The basis for the initial load distribution formulation used a Hertzian contact stress of 100 ksi to calculate the contact area. As the loading increased to 200 ksi the contact area (0.142 in/in) should have been increased. This is the benefit of using contact surfaces and deformable bodies as opposed to the approximated elemental pressure loadings used in this analysis. However, the Hertzian contact area is based on elastic theory. There is no allowance for load redistribution that occurs in an elastic-plastic analysis. This load redistribution provides for a smooth continuous residual compressive zone.

The localized point loadings observed are attributed to the starting and stopping of the simulated applied loadings. In the actual field application of the process, these sharp loadings/unloadings steps will be a smooth transition of increased loadings and rotation about the inner circumference. It is judged that these distinct localized alternating stress patterns will be mitigated if not eliminated completely. Only the stress patterns observed at the initial starting and final stopping points are considered to be possible conditions resulting from the process.

Summary

The computational results support the use of a 7" diameter, 2" thick plate with three equidistant support points for a proof-of-principle qualification mock-up. Small but measurable permanent deformation exists around the bore after roller burnishing, resulting in a relatively deep residual compressive stress state. The following additional conclusions are also drawn:

a) the hardening model selected influences the final stress state, with isotropic hardening generating less compressive stress results at the bore;

b) the kinematic hardening model results in stress patterns reflecting the starting and stopping points of the roller burnishing process that are not as pronounced as in the isotropic hardening material model;

c) the magnitude of the final stress state is a function of the material yield strength but the observed compressive stress state trend is still valid.

Table 1 Parameters Evaluated

Plate Diameter	**Weld Material**	**Base Material**	**Hardening Law**	**Boundary Condition**	**Loading**
7"	308	304	Isotropic	Uniform Restraint	Single Pass
		508Cl2	Kinematic	Single Point	Multi Pass
9"	308	304	Isotropic	Uniform/ Single Point	Single Pass

References

[a] "Computation of Residual Stress in Tubes Due to A Rolled Joint Forming Process"; Metzger, DR, Sauve, RG; ASME Pressure Vessel and Piping Conference Proceedings, Vol 235, pp 209-214 dated 1992

[b] "Prediction of Residual Stress by Simulation of the Rolled Joint Manufacturing Process for Steam Generators"; Metzger, DR, Sauve, RG, Nadeau, E; ASME Pressure Vessel and Piping Conference Proceedings, Vol 305, pp 67-74 dated 1995

[c] "Roller Burnishing of Hard Turned Surfaces"; F Klocke & J. Liermann; *International Journal of Machine Tools and Manufacture*; V38 N5-6; May-June 1998, pages 419-423

[d] "Effect of Expansion Technique and Plate Thickness on Near-Hole Residual Stresses and Fatigue Life of Cold Expanded Holes"; Ozdemir, AT& Herman R; Journal of Material Sciences, Vol 34 N6 p1243-1252, March 1999

[e] "Investigation into Roller Burnishing"; MH El-Axir; *International Journal of Machine Tools and Manufacture*; V40 N11; September 2000, pages 1603-1617

[f] "Experimental Techniques for Studying the Effects of Milling Roller Burnishing Parameters on Surface Integrity"; MM El-Khabeery & MH El-Axir; *International Journal of Machine Tools and Manufacture*; V41 N12; September 2001, pages 1705-1719

[g] Roark, RJ & Young WC, *Formulas for Stress and Strain*, McGraw-Hill Book Company, Fifth Edition

Appendix A – Contact Area Calculations

The initial contact area for applied loadings was calculated using Hertzian contact formulae. From Reference [g] Table 33 case 2c (a cylinder in a cylindrical socket) the following calculations were made.

Assume $E_1=E_2$ (modulus of elasticity of parts 1 and 2) and

$\upsilon_1=\upsilon_2=0.3$ (Poisson's ratio of parts 1 and 2) then

$b = 2.15[pK_D/E]^{1/2}$ and Max $\sigma_c = 5.91[pE/K_D]^{1/2}$ where

b = width of contact area σ_c = contact stress

p = load pre unit length

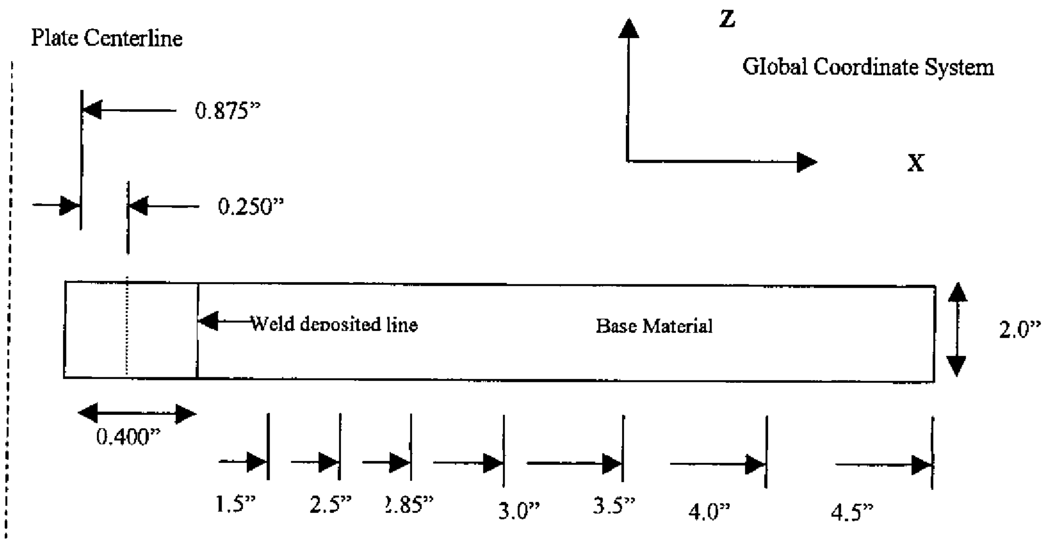
D_1 = diameter of bore = 1.75"

D_2 = diameter of roller = 0.435"

Where $K_D = D_1{*}D_2/D_1 - D_2$

Using E=29.0E6 and p = 100000 psi

Load (psi)	b (inches)
100000	0.100
125000	0.112
150000	0.123
175000	0.133
200000	0.142



Each dimension line represents a mesh change in the plane strain model

All dimensions taken from centerline of plate unless noted with a double arrow head

FIGURE 1 Cross-section of plate with model sections shown

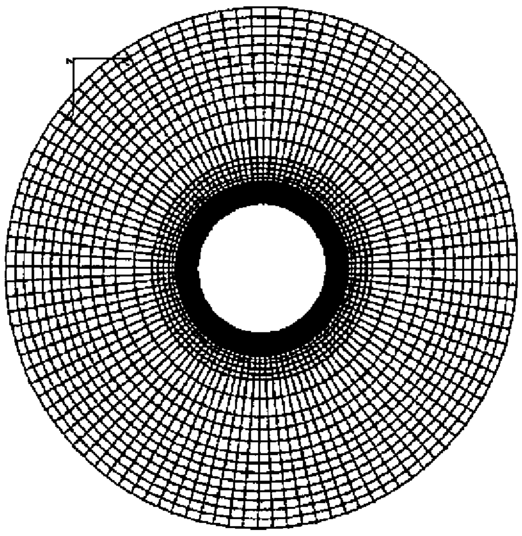


Figure 2 – Typical Basis Mesh

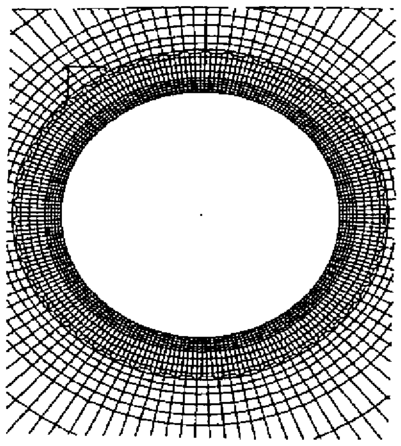


Figure 3– Typical Refined Mesh In Bore region

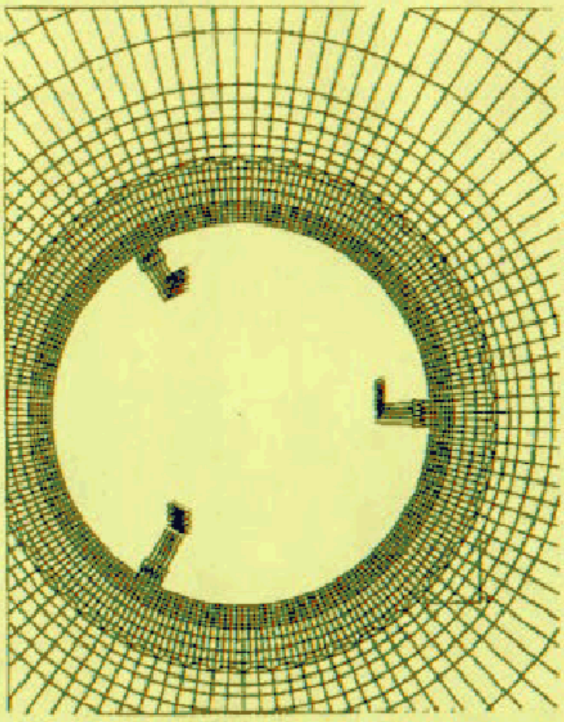


Figure 4 – Typical Loading

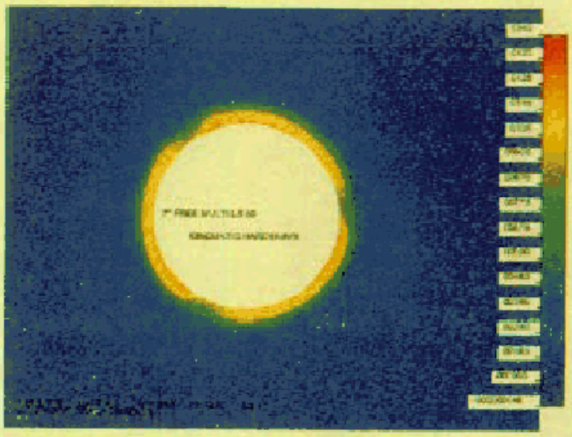


Figure 5 – 7" Dia. Fixed Edges, Kinematic Multiple Pass Case

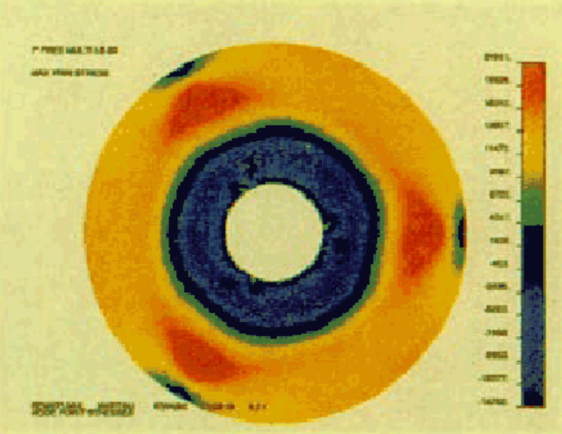


Figure 6 – 7" Dia. Three pt. Fix, Isotropic Multiple Pass Case

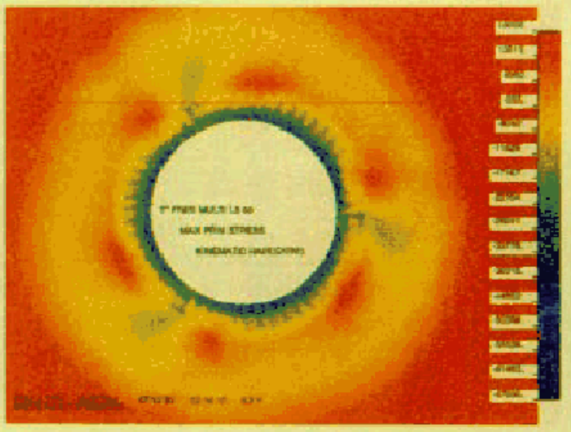


Figure 7 – 7" Dia.. Fixed Edges, Kinematic Multiple Pass Case