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Effect of Residual Stresses on Design Assessment of Partial Penetration Laser Welds in a Pressure Valve Component

A finite element analysis is conducted on a pressure component to determine the parameters for laser welding it

BY C. L. TSAI, M. L. LIAW AND J. I. TENG

ABSTRACT. An autogenous CO_2 laser weld joining a cap fitting to a valve body was analyzed using the ANSYS code. This stress analysis evaluated various weld penetration conditions from 0.02 to 0.04 in. The evaluation criteria included fracture, fatigue and general yielding of the weld at three load conditions: maximum operating pressure (500 lb/in.^{2}), proof pressure (750 lb/in.^{2}) and burst pressure (1250 lb/in.^{2}). It is concluded that, without considering welding-induced residual stresses, weld penetration of 0.02-in. (0.50 mm) is adequate for normal use of the investigated valve component. The factor of safety for 0.02-in. weld penetration is greater than four for the valve fitting. The residual stresses are found to affect the plastic zone size and shape. Weld shrinkage causes compressive radial stress at the weld root. The midsection of the weld penetration is in tension at radial, circumferential and longitudinal directions. The Von Mises equivalent stress in the weld is increased due to residual stresses, which reduces the safety factor by a range of around 40%. However, the factors of safety for all cases are still greater than three at rupture pressure. The root openings of the weld fitting with penetration greater than 0.02 in. are nonpropagating and fracture stable under the proof pressure due to the compressive residual stress surrounding the root opening. For a conservative design to relax the postweld inspection requirement or to prevent failure from an unexpected overloading situation, a minimum of 0.03-in. (0.76 mm) weld penetration is recommended for the cap fitting.

C. L. TSAI and M. L. LIAW are with The Ohio State University, Columbus, Ohio. J. I. TENG is with Marotta Scientific Controls, Inc.

Introduction

The construction of the valve component includes joining the cap, the outlet and the inlet fittings to the valve body using the laser welding process. This valve component is made of 316L stainless steel and designed for 500 lb/in.^{2} (3.4 MPa) maximum operating pressure. Autogenous CO_2 welds are made along the circumference of the fitting edges. During the proof tests, this valve component must sustain 750 lb/in.^{2} (5.2 MPa) proof pressure and 1250 lb/in.^{2} (8.6 MPa) burst pressure. Sufficient weld penetration is required to resist these pressures. The weld penetration ranging from 0.02 to 0.04 in. (0.50 to 1.0 mm) is recommended by the current design specifications. The allowable clearance between the fitting surfaces is 0.001 in. (0.025 mm).

KEY WORDS

Finite Element Analysis
FEM
Laser Welding
Valves
Pressure Test
Residual Stress
Fatigue Life

The ASME *Boiler and Pressure Vessel Code* (Ref. 1) provides the specification for pressure vessels in Section VIII and welding and brazing qualification in Section IX. However, this specification is focused on arc and gas welding. The requirements for laser welding are not mentioned. The objective of this study is to evaluate such requirements by a design analysis using the finite element method. This design analysis is based on a Failure Analysis Design concept (Ref. 2), which includes assessment of collapse and fracture behaviors of the welds. By the strength intensity factors obtained from the finite element analysis and Paris's Law (Ref. 3), the fatigue life of welds can also be predicted. The welding analysis between the cap and valve body is the subject of this investigation.

Material Properties

Material properties of the 316L used in this design analysis are summarized as follows:

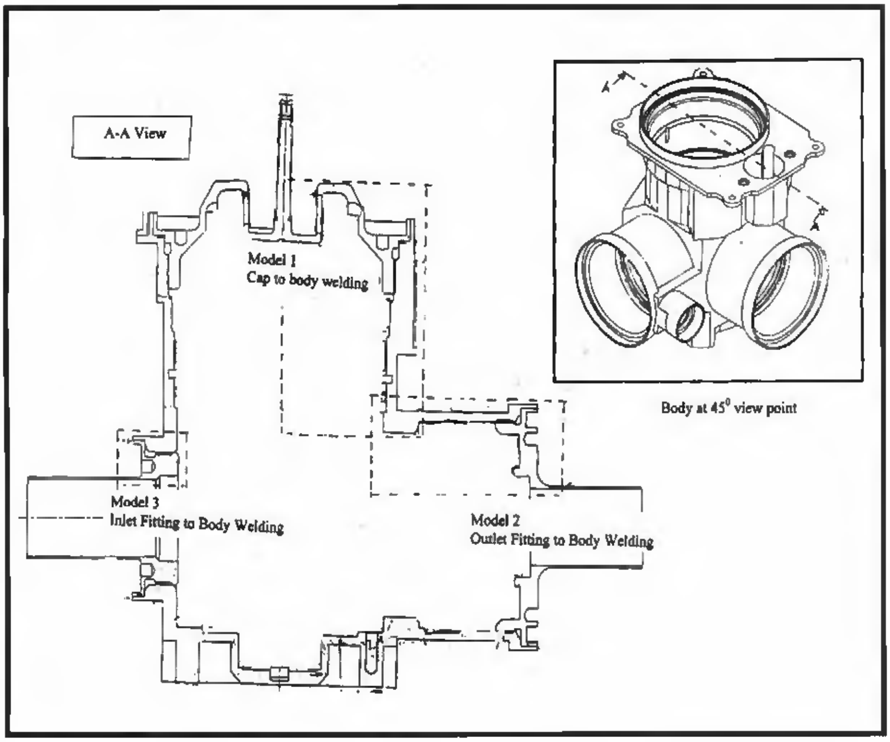

Fig. 1 — Axis symmetric components for finite element analysis.

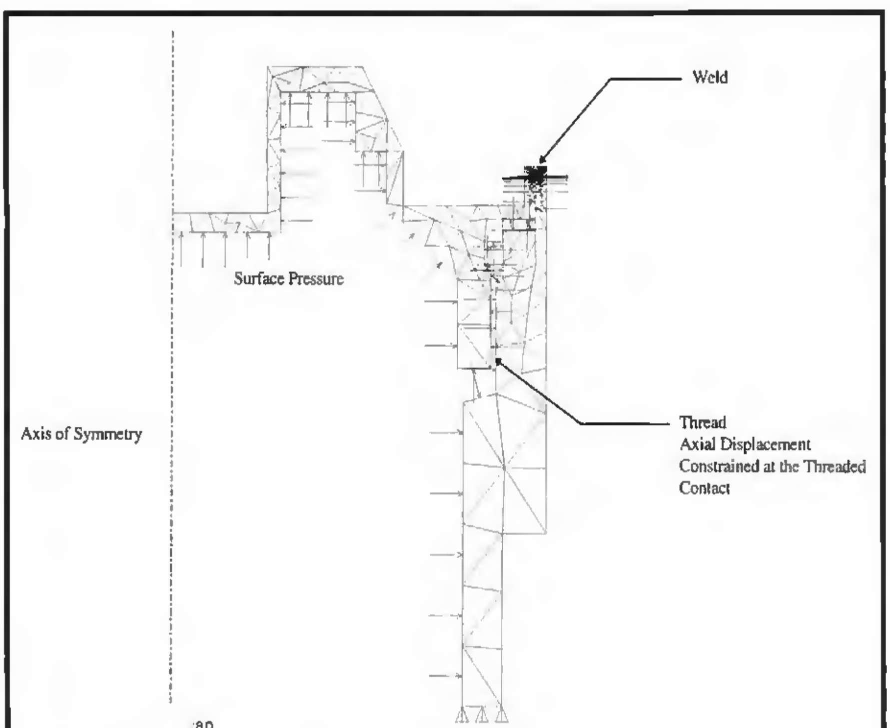

Fig. 2 — Finite element model for cap-to-body weld.

Mechanical Properties (Ref. 4). Minimum yield strength, 25 ksi (173.4 MPa); minimum ultimate tensile strength, 70 ksi (482.6 MPa); elongation for cold rolled, 40% and 45% for hot rolled; and 50% minimum reduction in cross-sectional area. For the flow stress-strain relationship, a linear strain hardening exponent of 0.165 is assumed. The flow stress-strain relationship terminates at fracture strain (0.4 strain).

Fracture Properties (Ref. 5). Charpy V-notch impact: 25 ft-lb (33.9 J), weld; 69 ft-lb (93.6 J), heat-affected zone; and 109 ft-lb (147.8 J), base metal, at –440°F (–262° C) and the translated critical stress intensity factor, using Barsom's two-stage and other methods described by Barsom and Rolfe (Ref. 3), would be 69 ksi $(in.)^{1/2}$ at the same temperature. In a real situation, the stress intensity factor will be much higher than 69 ksi $(in.)^{1/2}$ because the room or operating temperatures are much higher than –440°F.

Fatigue Properties (Ref. 3). Fatigue propagation threshold of steel is 5.5 ksi $(in.)^{1/2}$ for pulsating pressure variations and the fatigue crack propagation equation in room temperature and air environment is

$$da/dN = 3.0 \times 10^{-10} (\Delta K_I)^{3.25} \qquad (1)$$

where da is the amount of reduction of the weld penetration, dN is the number of pressure cycle increments, and ΔK_I is the stress intensity factor range.

Design Evaluation Criteria

The design variables analyzed in this project include 1) weld penetration varying from 0.02 to 0.04 in. and 2) pressure loading varying from 500 lb/in.^{2} to actual rupture pressure for each weld penetration in the cap fitting. The ANSYS finite element program (Ref. 6) was used for the stress analysis of each design condition. The design evaluation criteria consist of the following:

1) The minimum required weld penetration for all valve fittings is 0.02 in. This serves as a baseline for design evaluation.

2) Fracture of weld joints using the fracture mechanics parameters. The effective stress intensity factor and the estimated critical stress intensity factor of 316L stainless steel are used to evaluate the fracture behavior of the partial penetration weld joints. This criterion is to check if the partial penetration weld joints are stable. If the root openings are determined to be noncritical, no fracture from the root opening is anticipated.

3) Initial yielding at the root of weld penetration. Plastic deformation around the root opening is anticipated when the pressure level exceeds certain load magnitude. This pressure level is defined as yield load. Because of the singularity at the crack tip, the decision of yielding should be based on the nodal equivalent stresses around the crack. Local plastic deformation at the root opening is beneficial in preventing brittle fracture of the partial penetration weld joints because the plastic deformation and crack-tip blunting will increase the toughness (Ref. 9).

Table 1 — Factor of Safety, Residual Stress Effects not Considered

Weld Penetration (in.)	Ultimate/Design Load (500 lb/in.²)
0.020	4.76
0.025	4.97
0.030	4.92
0.035	5.00
0.040	4.97

4) General yielding around the welding area. The pressure load that causes the general yielding condition, which forms a plastic hinge at the valve body or fitting, is defined as ultimate load. The factor of safety is usually determined by dividing the ultimate load by design load.

5) Rupture of the valve due to maximum equivalent stress exceeding the ultimate strength, which is assumed to be the same at the weld and at the base material. This pressure load is defined as rupture load. The rupture load indicates the predicted burst pressure that would cause collapse of the welded components. This load is used to protect the valve system from rupture due to overload during normal operation.

6) Life expectancy of the welded components due to loading and unloading cycles during normal operation of the valve system. The root openings are either nonpropagating or would take a number of cycles to reduce weld penetration from 0.04 to 0.02 in., which is the penetration considered failure. If the stress intensity factor is greater than K_{IC} at a penetration depth larger than 0.02 in. during crack prorogation, the penetration depth should be considered as the critical depth and the fatigue life should be counted as cycles needed to reduce weld penetration from 0.04 in. to the critical penetration depth. This information is useful for inspection planning of the valve system.

Finite Element Model

Figure 1 shows the valve system from a 45-deg view and a plane view of the valve system. Three axisymmetric fitting components, cap, outlet and inlet are connected to the valve body. As mentioned previously, only the joint between the cap and valve body will be discussed. Figure 2 shows the finite element meshes and the boundary conditions of the fitting component isolated from the valve system for analysis. Refined meshes were used in the weld area and singular elements were used around the tip of the root opening — Fig. 3. A root opening of 0.001 in. was used in the models. The boundary conditions include pressure

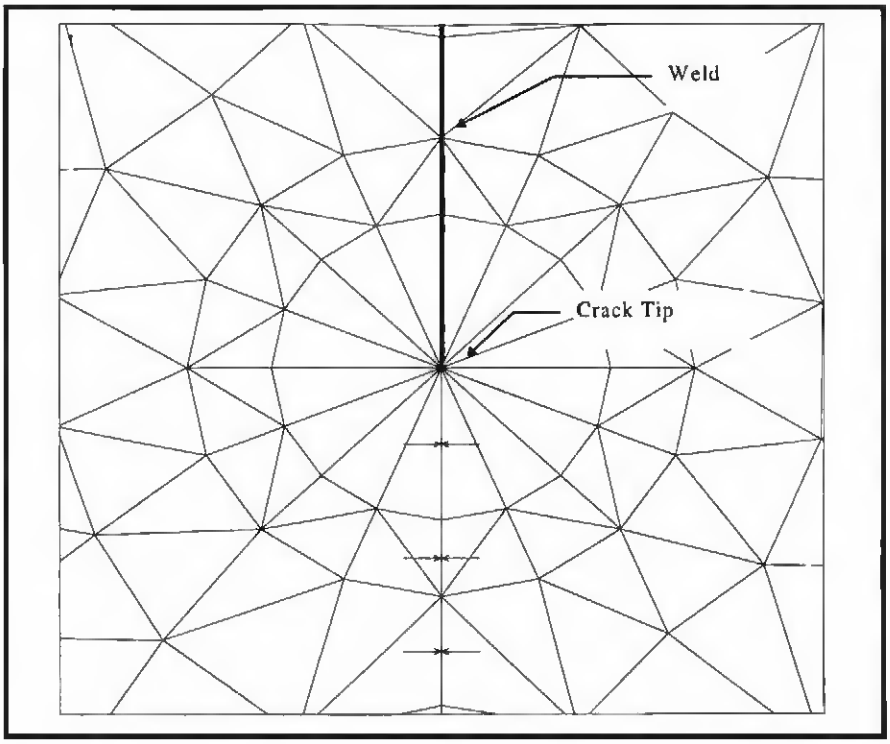

Fig. 3 — Refined crack-tip model.

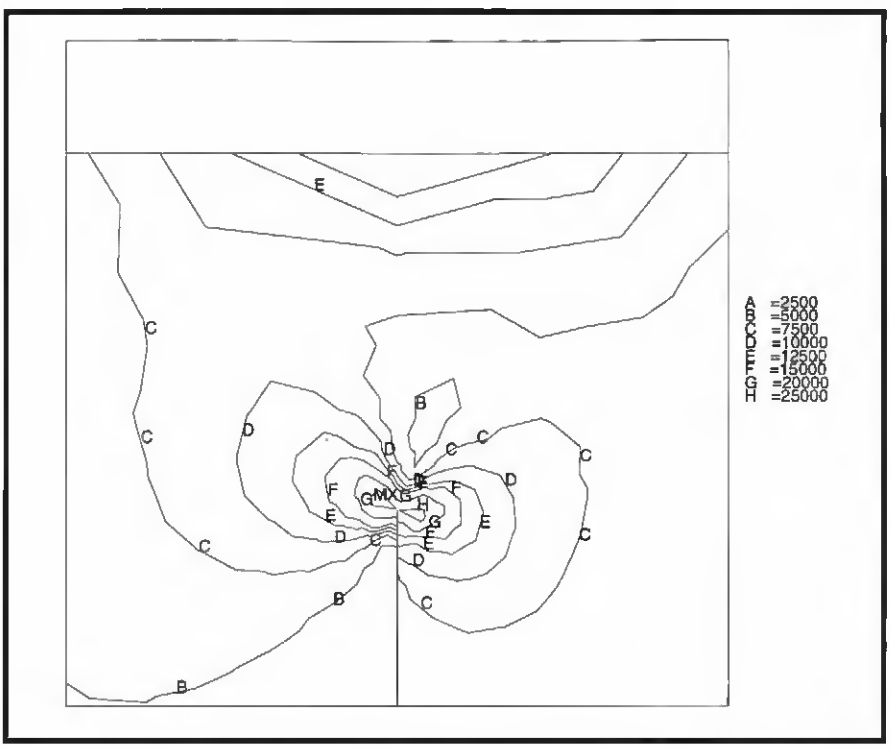

Fig. 4 — The Von Mises equivalent stress at the crack tip (weld penetration, 0.02 in.; stress unit, lb/in.²).

loading at the internal surfaces, axisymmetry along the central axis, restraint in the axial (parallel to the axis of symmetry) displacement at the threaded contact points, and simple supports along the cut-off sections of the finite element analysis (FEA) model. The ANSYS code was used for the analysis.

The six-node triangular solid elements (ANSYS plane two-element type) were

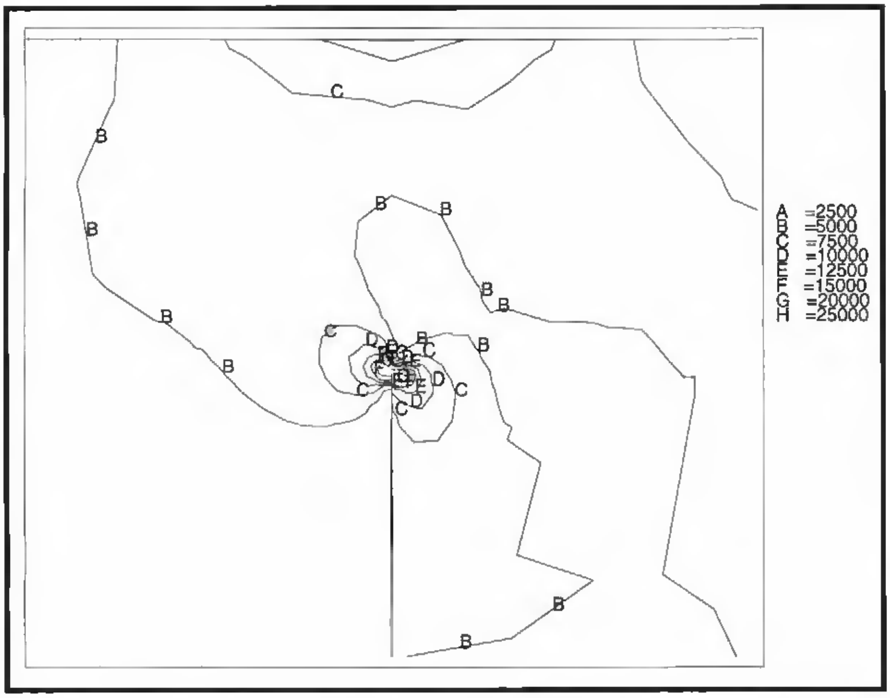

Fig. 5 — The Von Mises equivalent stress at crack tip (weld penetration, 0.04 in.; stress unit, lb/in.²).

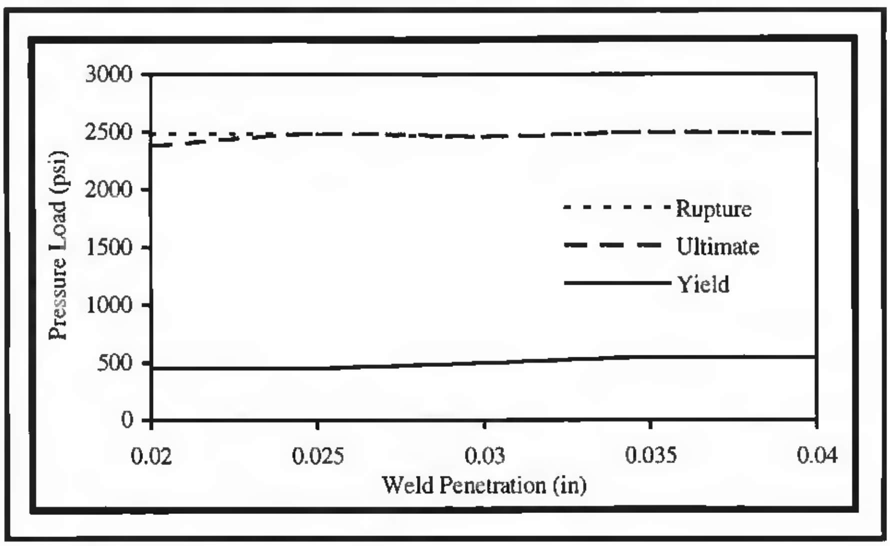

Fig. 6 — Cap failure load vs. weld penetration.

used in the models. This type of element has quadratic displacement shapes, which fit well with the irregular boundary geometry. These types of elements can be assigned as either plane stress, plane strain or axisymmetric elements with or without thickness input. The axisymmetric condition was assigned to the element in this design analysis. The singular point at the crack tip was treated by the concept of quarter-point element (Ref. 8). This is a conventional finite element in which the mid-side node is shifted to reflect the $1/\sqrt{r}$ singular behavior in elastic crack problems. The stress in the crack tip is calculated by extrapolating the stresses at the nodes around the crack tip.

The stress intensity factors were also obtained by extrapolation (Ref. 6). The following are the procedures to calculated K_I, which is the stress intensity factor for opening mode. The stress intensity factor for sliding mode and tearing mode, K_{II} and K_{III}, can also be derived by similar procedures.

Let node point I be the crack tip and points J and K be the node points on the crack just before point I. The displacement (V) that is normal to the crack is (Ref. 9)

$$V = \frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}(1+k) \tag{2}$$

where G is shear modules, r is the radius from the crack tip and k = 3–4v for plane strain and

$$k = \frac{3-v}{1+v}$$

for plane stress. For symmetry at the crack plane, Equation 2 can be reorganized to give

$$K_I = \sqrt{2\pi}\,\frac{2G}{1+k}\,\frac{|v|}{\sqrt{r}} \tag{3}$$

For nonsymmetry, Equation 2 will be

$$K_I = \sqrt{2\pi}\,\frac{G}{1+k}\,\frac{|\Delta v|}{\sqrt{r}} \tag{4}$$

where Δv is the motion of one crack face with respect to the other.

Assuming that

$$\frac{|\Delta v|}{\sqrt{r}} = A + Br \tag{5}$$

and calculating A and B by the displacements of point J and K, then the stress intensity factor at the crack tip can be represented as

$$K_I = \lim_{r\to 0}\sqrt{2\pi}\,\frac{G}{1+k}(A+Br) \approx \sqrt{2\pi}\,\frac{G}{1+k}A \tag{6}$$

For elastic-plastic analysis, instead of the stress intensity factors K, the J-integral around the tip is the criterion to determine fracture. Assuming that the crack lies in the globe Cartesian X-Y planes, with X parallel to the crack, the J-integral can be expressed as Equation 7

$$J = \int_\Gamma W dy - \int_\Gamma \left(t_x \frac{\partial u_x}{\partial x} + t_y \frac{\partial u_y}{\partial y} \right) ds \tag{7}$$

where Γ = any path around the crack tip, W = strain energy density, t_x = traction vector along x axis = $\sigma_x n_x + \sigma_{xy} n_y$, t_y = traction vector along y axis = $\sigma_y n_y + \sigma_{xy} n_x$, σ = component stress, n = unit outer normal vector to path Γ, s = distance along the path Γ.

After the J-integral is obtained from the results of stress analysis, the effective stress intensity factor can be calculated by the following formula:

$$J = \frac{1}{E'}\left(K_I^2 + K_{II}^2\right) + \frac{1}{2G}K_{III}^2 \tag{8}$$

where E′= E for plane stress and E′= E/(1-v^2) for plane strain and axis symmetry.

The inherent shrinkage strain method (Ref. 7) was applied to calculate the residual stresses. A thermal analysis was performed first by assuming that the initial temperature at the weld was 1500°F (816°C) and the base metal and surrounding air had initial temperature 70°F

(21.1°C). The temperature-dependent material properties, such as conductivity, specific heat and thermal expansion coefficient, were considered in the analysis. The temperature at the weld gradually cooled down to the room temperature (70°F) because of the effects of conduction and convection. The temperature distributions during the cooling period were considered as the thermal loads in stress analysis. An elastic-plastic analysis procedure was performed to determine the equilibrium between the weld shrinkage and the structural rigidity of the valve fitting.

Results and Discussion

Two FEA procedures, linear-elastic and elastic-plastic, were conducted in this study. The linear-elastic analysis was to determine the stress intensity factors of opening mode (K_I) and sliding mode (K_{II}), as well as their combined effect on weld fracture using the effective stress intensity factor (K_{eff}). The elastic-plastic analysis was used to determine the yield load, the ultimate load and the rupture load of the weld joints. It was also used to determine the residual stresses and their effects on the J-integral and the effective stress intensity factor.

The discussions below consist of results without the consideration of residual stresses and results with the consideration of residual stresses.

Results without the Consideration of Residual Stresses

Von Mises Equivalent Stress Map

Figures 4 and 5 show the equivalent stress maps in the weld section of the cap valve fitting at the design load (maximum operating load at 500 lb/in.²). Only the results from analysis of two weld penetration depths, 0.020 and 0.040 in., are shown. Equivalent stress distributions for other penetration depths have a similar pattern, but the size of the constant stress zones falls between these two extreme penetration cases.

The average equivalent stress in the weld section is between 5 and 10 ksi. Higher stress areas are at the root of the weld and at the top surface. The maximum stress for 0.040-in. weld penetration is between 20 and 24 ksi at the weld root and is less than 15 ksi at the top surface. For 0.020-in. weld penetration, the maximum stress is approximately yield stress (25 ksi) at the weld root where a small amount of plastic deformation is present. Stress at the top surface is between 15 and 20 ksi. The high-stress zones are small in both penetration cases.

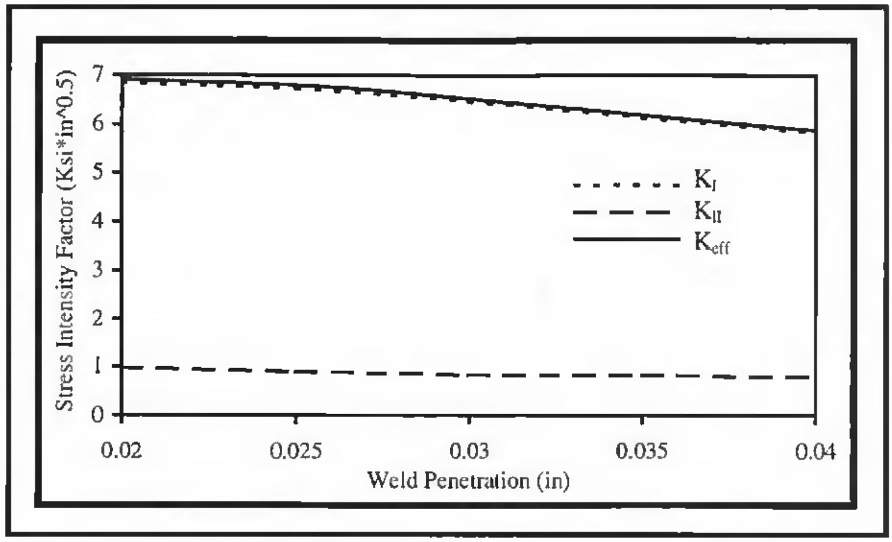

Fig. 7 — Stress intensity factor vs. weld penetration.

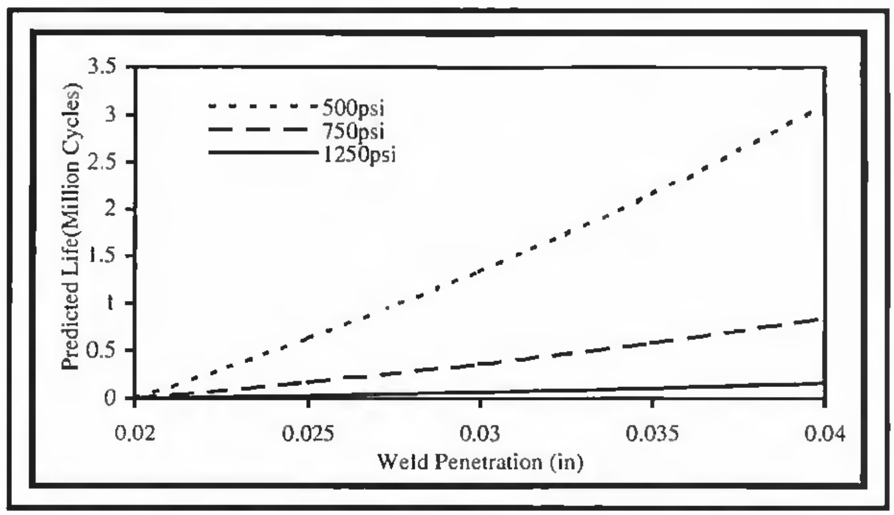

Fig. 8 — Cumulative load cycles needed for weld penetration, decreasing to 0.02 in.

Table 2 — Summary of J-Integral and K_{eff} at Cap with Considering Residual Stress Effects

Weld Penetration	0 lb/in.²		500 lb/in.²		750 lb/in.²		1250 lb/in.²	
(in)	J	K	J	K	J	K	J	K
0.020	−1.95	0	−0.85	0	−0.16	0	123	61.77
0.025	−2.42	0	−1.43	0	−0.96	0	130.96	63.59
0.030	−2.96	0	−2.40	0	−2.16	0	111	58.59
0.035	−2.56	0	−2.13	0	−2.28	0	107.64	57.65
0.040	−3.05	0	−2.52	0	−2.63	0	109.51	58.15

Unit : J : in-lb/in²; K_{eff} : Ksi $\sqrt{in}$.

From the stress pattern at the root of weld penetration, the tensile stress is significant in opening up the root. This root opening is also subject to a strong influence of shear stresses. This is referred to as Mixing Mode fracture characteristics.

Load Parameters for Design Evaluation by Elastic-Plastic Stress Analysis

Figure 6 shows three load parameters for design evaluation of various weld penetrations. The rupture loads and ultimate loads are almost at the same value of 2500 lb/in.². This is because the large strain will occur when the plastic hinge is formed. The yield load is below 500 lb/in.² when the penetration is less than 0.030 in. When the penetration is larger than 0.030 in., there is no yielding under the operating pressure (500 lb/in.²). It is common engineering practice to consider the ultimate load as the limiting capacity of the valve compo-

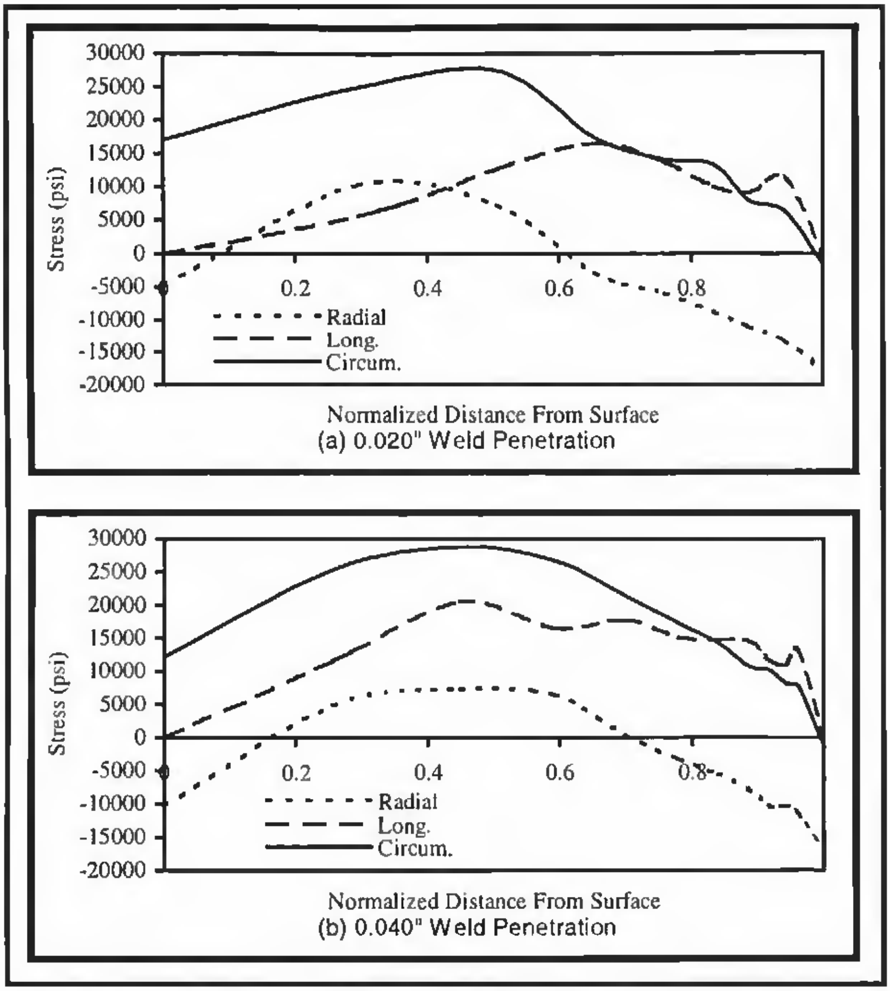

Fig. 9 — Distribution of radial, circumferential and longitudinal residual stresses along the cross section of the cap weld fitting.

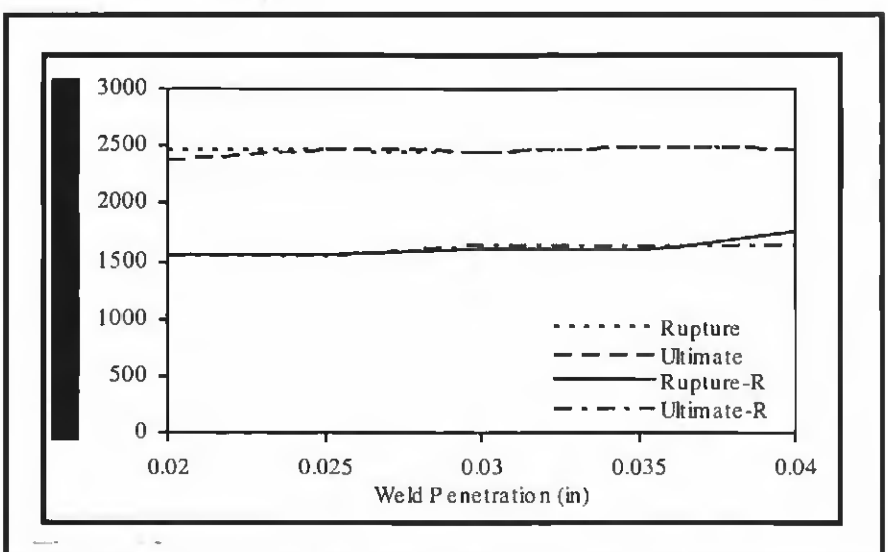

Fig. 10 — Effect of residual stress on rupture load and ultimate load (cap fitting).

nents to sustain the pressure. The rupture load is typically used for a safeguard to prevent rupture of the components from unexpected overloading. It is also used to relax the quality control requirement during manufacturing of the valve system. Yield load is used to determine when the weld section will begin the plastic deformation process. Local plastic deformation stabilizes the root opening due to blunting the opening tip. Excessive yielding conditions in the weld section are guarded by checking the ultimate load. Therefore, no alarm is necessary if local plastic deformation is shown at the root of the weld penetration, as the general yielding failure is the only concern. For fracture and fatigue analysis, attention should be given to the local high-stress zone because stress concentration will affect the fatigue and fracture characters.

To determine the safety factor of various weld penetrations in the valve component, the ultimate loads are divided by the design load, which is the maximum operating pressure at 500 lb/in.^{2}. Table 1 summarizes the factor of safety values. The factor of safety varies from 4.76 (0.020-in. penetration) to 5.00 (0.035-in. penetration). The factor of safety commonly used in engineering design is between 1.5 and 2 depending on the confidence level with respect to the reliability issues. Therefore, any weld penetrations 0.02 in. or more are acceptable.

Figure 6 and Table 1 show that the ultimate loads for the weld fittings are decreased when the weld penetration is increased from 0.035 to 0.040 in. This may be caused by the numerical reasons or geometrical changes around the crack tip as the penetrations change. Nevertheless, this observation will not affect the conclusions in the overall design evaluation.

Fracture Stability of Partial Penetration Welds

Figure 7 shows the stress intensity factors at the root opening tip of the weld at the burst pressure of 1250 lb/in.^{2}. The stress intensity factors were plotted vs. the weld penetration.

All predicted stress intensity factors are less than 11% of the critical stress intensity factor of 316L stainless steel, which is 69 ksi (in.)$^{1/2}$ at –440°F and is expected to be greater than the value at room or higher temperatures. Therefore, it is concluded that any weld penetrations 0.020 in. or more are free of sudden fracture under the burst load at 1250 lb/in.^{2}.

To determine any penetration reduction due to cyclic pressure variations during service life of the valve system, the effective stress intensity factor range, ΔK_{eff}, is compared with the fatigue propagation threshold, which is 5.5 ksi (in.)$^{1/2}$ for 316L stainless steel. Weld penetration in the cap welds may be reduced by growth of the root opening toward the top surface under the repeated pressure variations.

Paris's crack propagation law for austenitic stainless steel was used to determine the root opening growth. The effective stress intensity factor ranges for the propagating root openings were determined numerically from Fig. 7. An integration procedure using Paris's crack propagation law was then conducted over the penetration depth range from 0.04 to 0.02 in. with a decrement of 0.005 in. (0.127 mm). Figure 8 shows the cumulative pressure load cycles needed for any of the intermediate penetration depths, propagating to the final 0.02 in. in the cap welds. Under normal operating conditions (not exceeding 500 lb/in.^{2} maximum operating pressure) it would take approximately 3 million cycles for the cap weld to reduce the penetration from 0.04 to 0.02 in.

Results with the Consideration of Residual Stresses

Residual stress comes from shrinkage of the weld. To show typical stress distributions, the residual stresses along the weld centerline in the cap fittings were plotted against the normalized weld penetration in Fig. 9. The zero distance represents the weld surface and the unit distance represents the root of the welds. Three stress components, longitudinal, radial and circumferential, were plotted for the 0.02- and 0.04-in. penetration cases.

The longitudinal stresses are in tension with their maximum near the midsection of the weld. The magnitudes of the maximum stresses are 15 ksi for 0.02-in. weld penetration and 20 ksi for 0.04-in. weld penetration. The circumferential stresses are in tension and are maximum near the midsection of the weld. The radial stresses are in compression at the weld surface and the weld root. The mid-weld sections are in tension. The sum of radial stresses along the weld interface should be zero to satisfy the equation of force equilibrium. This provides a convenient tool to check the results of stress analysis.

Residual Stress Effects

Figure 9 shows high compressive stresses at the weld root in a radial direction. It implies that the residual stress could close the root opening, improving the fracture stability at the root. Table 2 shows the J-integral and effective stress intensity factors at different loads. It can be observed that, when the load is less than 750 lb/in.^{2}, the J-integral is negative, which means that the compressive radial residual stress keeps the root opening closed and no fracture is expected. When the applied load is large enough (*e.g.*, 1250 lb/in.^{2}), the compressive residual stress will be overcome by the load, which tends to open the root. The outward load will interact with the tensile residual stress at the midsection of the weld, so the effective stress intensity factors will be larger than the factors that do not consider residual stress. Although the effective stress intensity factor becomes larger, it still is less than the critical stress intensity factor. Therefore, the valve is stable at burst pressure.

Because the residual stresses induce yielding around the welds, the Von Mises equivalent stresses are higher and high-stress zones spread in a broader area. With the effect of residual stresses, the threshold design pressures are reduced due to expansion in the plastic zones in the weld. Figure 10 shows the comparisons of the load parameters with and without the consideration of residual stresses in the finite element analysis. It shows the ultimate loads and rupture loads will reduce to around 1500 lb/in.^{2}, which is a 40% reduction of the safety factor. However, the factors of safety for all cases are still greater than three at ultimate load. It means that the current design can provide sufficient strength under the design load whether residual stress is considered or not. For a conservative design to relax the postweld inspection requirement or to prevent failure from an unexpected overloading situation, a minimum of 0.030-in. weld penetration is recommended for the cap fittings.

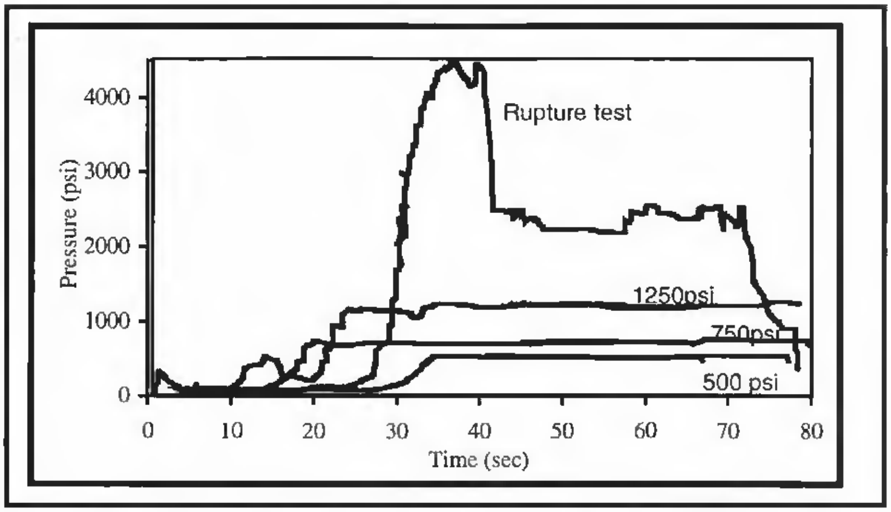

Fig. 11 — Experiment results of cap and value body joint under different loads.

Experiment Verification

The joined cap and valve body was tested under 500 lb/in.^{2} design load, 750 lb/in.^{2} proof load and 1250 lb/in.^{2} burst load. Hydraulic oil was used to pressurize the component. After reaching the expected pressure, the pressure was held more than one minute to observe and record any visible rupture. Figure 11 shows the pressure change during these tests. Variation is very small after pressure reached the expected values , implying the current design for weld penetration can resist the applied loads. These results verify the finite element model (FEM) analysis.

A fatigue test was also perform under the design load (500 lb/in.^{2}). The pressure was gradually increased from 0 to 500 lb/in.^{2} and backed to 0 lb/in.^{2} for 1000 cycles with hydraulic oil. Any visible outside damage was recorded. The fatigue test shows the component can operate more than 1000 cycles under the design load. This result also matches the FEM's life perdition.

The maximum load that the component can resist was obtained by pressurizing the component with hydraulic oil until it ruptured. Figure 11 shows the maximum load is about 4450 lb/in.^{2}. The rupture pressure is higher than the predicted pressures from FEM analysis, which were about 2500 lb/in.^{2} when residual stress was not considered and 1500 lb/in.^{2} when residual stress was considered. The predicted rupture pressure was decided as the lowest load that has the stress higher than the tensile strength of the material. This is a conservative prediction because more load is needed for total rupture after the incipience of plastic fracture. Another reason of the difference perhaps comes from the change of material properties during processing and assembling. Although there is some difference, the results from FEM analysis can provide the lower band of rupture load.

Conclusions

Several conclusions can be obtained from the FEA results.

1) No welds within the specified penetration range of 0.02 to 0.04 in. will fracture at the burst pressure (1250 lb/in.^{2}).

2) The minimum factor of safety of welds in the valve body at the maximum operating pressure is three.

3) Any weld penetration 0.030 in. or more will not result in plastic deformation under the maximum operating pressure (500 lb/in.^{2}). At this pressure level, yielding just begins to occur at the weld root if the penetration depths are smaller than 0.030 in.

4) Under repeated loading and unloading pressure variations between zero and 500 lb/in.^{2}, it would take 3 million cycles for the cap weld to reduce its weld penetration from 0.040 to 0.020 in.

5) No failure is anticipated to occur in any of the weld penetrations 0.020 in. of more during proof testing.

6) Welding-induced compressive residual stresses will stabilize the crack at the root of the weld when the pressure is low. When the applied pressure places the weld root in tension, the outward load will interact with the tensile residual stress at the midsection of the weld to make the component more fracture sensitive.

7) Residual stress will change the plastic zone's size and pattern. Due to the expansion of the plastic zone, the ultimate load and rupture load of the welding component will decrease.

8) It is concluded that weld penetration of 0.02 in. in the valve fittings investigated in this project is adequate for normal service use. However, for a more conservative design to relax the postweld inspection requirement or to protect the valve system from unexpected overloading, a minimum of 0.030-in. weld penetration is recommended.

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