An Analytical and Experimental Study of the Effects of Welding Parameters on Fusion Welds

The effects of welding parameters upon the deformations and residual stresses produced by circular welds on thin plate are examined

BY B. K. JONES, A. F. EMERY AND S. J. MARBURGER

ABSTRACT. A major concern in welding structures is the determination of a proper welding procedure, i.e., travel speed, power and preheat, in the presence of external mechanical constraints or constraints self-induced by the structure’s shape. This paper discusses a study to characterize the effects of certain parameters upon the deformations and residual stresses produced by circular welds on a thin plate. In this work, relatively simple modeling assumptions are used to gain insight into the behavior of welded structures. The temperatures, distortions and residual stresses predicted by the models are verified by comparison to baseline experiments. The models are then used to explore the effects that factors such as heat sinking, preheating and geometry have on the deformations and residual stresses in the workpiece.

Introduction

How welding parameters are varied in order to minimize distortions and residual stresses is more an art than a science. Currently, despite continuous advances in analyzing the welding process, only broad generalizations are available about the link between the welding procedure and the mechanical behavior of the weld. It is known, for instance, that preheating will generally reduce the residual stresses in a weldment. The amount of reduction, however, as well as the interaction of preheating with other factors is not generally quantified. Likewise, the use of heat sinks at the boundaries of the weldment can change the heat flow and associated distortions. But knowing where and when to use heat sinks and gauging their effect has traditionally involved more intuition than engineering science. In many situations, the design criteria are flexible enough that such generalizations can easily be used to specify the welding parameters. In other situations, however, the criteria may be so tightly fixed that the trial and error approach typically used in specifying the procedure becomes inappropriate. For these situations, it is important that the welding parameters be precisely characterized if the design criteria are to be met.

To precisely characterize the welding parameters is a difficult task. The parameters vary widely and are highly interactive, the physics of the process is complex, and the design criteria change according to the application of the weld. A number of weldability tests have been developed to characterize materials with respect to various criteria. The Lehigh test (Ref. 1) is used to evaluate a material welded under various levels of restraint. Savage and Lundin (Ref. 2) developed the Varestraint test to evaluate a material’s propensity for hot cracking. Hackett and Seaborn (Ref. 3) developed a circular patch test which David and Woodhouse (Ref. 4) have modified to evaluate hot cracking in thin sheet materials. These tests, while providing useful qualitative information about the criteria in question, are purely empirical. The results of a Varestraint test, for instance, can only be compared to results from other Varestraint tests. Relating those results to an actual design situation is much more difficult. Likewise, the modified circular patch test (Ref. 4) sets some very simple conditions by which a material is judged to be “weldable,” “susceptible to cracking” or “highly susceptible to cracking.” No attempt is made, however, to relate the conditions under which the specimen cracked to the thermal or mechanical state of the test sample. Again, it becomes difficult to apply the results of the test to an actual design.

On the other hand, the complexity of the welding process, combined with an increasing emphasis on computational methods, has led to some very sophisticated welding models. Various studies have modeled details of the molten weld pool, microstructural changes, three-dimensional thermal and mechanical behavior, etc. An ideal welding model would be able to take as input basic parameters—the geometry, boundary conditions, welding speed, power, etc.—and, based solely on the principles of mechanics, predict the transient behavior of the process. This ideal, of course, is far from being realized, and numerous pitfalls exist. For instance, computation times, even with supercomputers, increase dramatically as the level of detail within an analysis increases. Obtaining direct experimental verification of computed results can also be more complicated than formulating the models themselves. A sophisticated model may account for numerous factors within the welding process, but the effects that are modeled may be extremely difficult or even impossible to confirm experimentally.

The objectives of this work are twofold: The first is to use some rela-
tively simple numerical techniques to model the global thermal and mechanical behavior of welded structures and to verify those models with some direct experimental comparisons. The second is to use those models to determine how some of the basic welding parameters and mechanical constraints affect the thermal and mechanical behavior. The geometry shown in Fig. 1, which is similar to the circular patch test, was chosen for the following reasons:

1) The geometry is representative of a typical manufacturing situation. The analytical methods used here can be applied to similar industrial applications.

2) The thickness of the plate is small (0.2 cm/0.08 in.), minimizing through-thickness effects and allowing the global temperature and stress fields to be represented as two-dimensional. The outer edge of the boss (Fig. 1) is unconstrained, eliminating modeling uncertainties, yet the circular geometry provides a high degree of internal restraint.

3) With this geometry, similar tests can be developed to judge the performance of a weld under known states of temperature, distortion and stress. Such tests could be used to simulate full-scale welds and to reduce the number of mockups used in developing new prototypes.

Our aim in this study is to establish some baseline simplifying assumptions that can be used in computing the global thermal and mechanical behavior of welded structures. By limiting our focus to relatively simple models based on well-established numerical techniques, we hope to obtain an intuitive understanding of the process without getting lost in the details of the calculations. The following sections will discuss our analytical approach and describe the experiments that were performed to verify the analyses. We will then show some specific examples of how the analytical model can be used to gauge the effect of welding parameters on the mechanical behavior, and how those parameters can be used to manipulate the thermal behavior, distortions and residual stresses.

Previous Experimental and Analytical Comparisons

In most welding analyses, performing the calculations is by far the easiest part of the problem. Verifying the calculated results and drawing appropriate conclusions from those results is much more difficult. Obtaining reliable experimental data in a welding test can be particularly difficult due to the severe environment that instrumentations is subjected to. Some relevant studies are listed below.

In an early attempt at using finite element methods to analyze the welding process, Hibbitt and Marcal (Ref. 5) modeled a circular weld bead on a ½-in.-thick plate. The geometry was modeled axisymmetrically by assuming that the temperature distribution was pseudo-steady state, i.e., that each radial cross-section of the plate experienced essentially the same temperature history. The computed residual stresses were compared to an experimental conducted earlier by Corrigan (Ref. 6). The comparison was ambiguous at best — Corrigan reported values assuming no variation through the plate's thickness while Hibbitt and Marcal reported the range of stress through the thickness. In some locations, Corrigan's values were within the predicted range, in other cases they were well outside it. No comparisons were shown for thermal behavior or distortions.

Jonsson, Karlsson and Lindgren (Ref. 7) conducted an analytical and experimental comparison of butt joint welding on large plates. They assumed that the temperatures, stresses and strains were constant through the thickness and, similar to Hibbitt and Marcal, that the temperature distribution was pseudo-steady state. Three mechanical measurements were made: the gap width ahead of the weld pool; transient strains using gauges near the weld bead; and residual stresses using hole drilling techniques. The measured and analytical gap widths were very close to each other, while less conclusive agreement was obtained for the transient strains and residual stresses.

Andersson (Ref. 8), and Papazoglou and Masubuchi (Ref. 9) conducted analytical and experimental studies of butt joint welding on large plates in which phase transformation effects were emphasized. Neither study, however, demonstrated experimentally any such effects. Andersson's only experimental data were measurements of residual stress from hole drilling techniques that agreed qualitatively with his analysis. Papazoglou and Masubuchi compared the transient strains at a point near the fusion zone, obtaining good agreement.

The residual stresses in girth welded pipes have been the subject of numerous studies (Refs. 10-14). All of the studies listed here modeled the pipe axisymmetrically. Experimental stresses were generally determined by using relaxation techniques and, at best, agreed qualitatively with analytical values. Rybicki (Ref. 10) also compared experimental and analytical deformations, showing good agreement.
A review of these studies will show some common themes. First, the thermal computations are not true predictions of the measured values. The complex nature of the heat source/weld pool interaction has, to date, prevented any reliable prediction of the overall thermal behavior based solely upon the welding parameters (i.e., arc current, voltage, welding speed, etc.). Analysts typically vary aspects such as the "arc efficiency" or the thermal properties of the weld pool until the computed behavior matches the experiment. This is not to say that the computed values are purely empirical, but simply that current models of welding heat sources require some type of empirical input. Second, the experimental data used to confirm analytical predictions are extremely limited. Although temperatures outside the fusion zone can easily be measured using thermocouples, the measurement of transient deformations and residual stresses can at best be described as cumbersome. In general, spatial resolution is extremely poor (most relaxation techniques for residual stresses, for instance, are based on small stress gradients), results often depend upon the measurer and tests are time consuming and expensive to conduct. Finally, it is difficult to obtain experimental data which directly verify the gross assumptions of an analysis. Verifying fine details, such as microstructural changes or weld pool assumptions, is often impossible.

Experimental Approach

The primary role of the experiments in this study is to verify the analytical models. Four field variables are used as the criteria in judging the models: temperatures measured with thermocouples; displacements measured with the use of fiducial marks; transient strains measured with high-temperature strain gauges; and residual stresses estimated using hole-drilling methods. A typical experiment is run as follows: the test sample of Fig. 1 is placed in an automated gas tungsten arc (GTA) welding fixture inside an argon atmosphere welding box. A continuously cooled water jacket is in constant contact with the boss and provides a nearly constant temperature boundary condition. The initial temperature of the plate and the temperature of the water jacket is 10°C (50°F). Fiducial marks are made at a radial spacing of 0.64 cm (0.25 in.) on eight radial lines, spaced every 45 deg. By measuring the location of these marks before and after welding, point values of the entire displacement field are determined. An array of thermocouples is attached to the surface of the plate to obtain transient temperature measurements. In most cases, the thermocouples are attached in a circular array, with one circle located ½ in. inside the weld radius, and another circle located ¾ in. outside the weld radius. A thermocouple is also placed at the center of the sample. The sample is welded at a constant speed. In some experiments, the weld bead is simply applied to the solid plate. In other cases, a narrow groove (0.05 cm/0.20 in. wide) was initially machined into the plate to better simulate the joining of two parts. The portion of the plate inside the groove is held in place by eight narrow webs that provide very little mechanical connection between the two parts. After the bead is applied, the sample remains inside the water-cooled jacket until it reaches thermal equilibrium.

The sample material is 304L stainless steel with a yield stress of 280 MPa (41 ksi). The welding speed for the tests shown here is 6 cm/min (2.36 in./min). The weld radius varied from 2.5 to 5.1 cm (0.98 to 2.0 in.). In each test, the applied potential was constant at 8 V, and the current was varied such that the width of the weld bead was a constant 0.6 cm (0.2 in.).

Experimental errors for thermocouple measurements are well characterized and will not be discussed here. Displacement errors were characterized by comparing duplicate measurements of the fiducial array on a test sample. The measurements matched to within 0.0002 cm (0.0008 in.). Errors associated with the strain gauge and residual stress measurements are less defined. During welding, it was observed that the temperature in the strain gauge region was high enough to allow the epoxy to creep — exactly how much is unknown. The strain gauge results, however, are still useful for a qualitative comparison, which will be shown later with the analytical/experimental results. Residual stress measurements were conducted according to Technical Note TN-503-3 published by Measurements Group, Inc. (Ref. 16). Since significant errors can be introduced from a number of sources, the results are best interpreted as an estimate.

Analytical Approach

The complexity of the welding process has inspired a wide variety of modeling approaches, each with its own set of assumptions. The computational process for residual stresses, however, is...
Fig. 4 — Temperature vs. time for the analysis and three replicate experiments. The thermocouples in Sectors 1 and 2 were located at a radius of 2.54 cm. The welding arc was extinguished at approximately 250 s.

Fig. 5 — Left—Magnified experimental deformations; right—magnified analytical deformations. (X 15)

straightforward: Perform a thermal analysis to obtain the global temperature history of the model, then use the temperature distributions at discrete steps as the driving input for the mechanical model. Three difficulties distinguish an analysis of the welding process from other thermal stress analyses — the geometry of the weldment, the molten weld pool and the material behavior at elevated temperatures.

Typically, the geometries for practical welding problems involve three-dimensional fields of temperature, stress and strain. Even for the case of Fig. 1, quantities in the immediate region of the weld bead most likely will not be constant through the thickness. The width of the weld bead, for example, was, in general, slightly larger on the top of the test samples than on the bottom. Likewise, microstructure variations at the fusion zone boundary could negate any plane stress assumptions in that region. Figure 2 shows the measured radial displacement profiles for three circumferential locations on the top and bottom surfaces. A comparison of the top and bottom profiles shows a slight variation with thickness near the weld bead. The global behavior, however, shows good consistency with the thin-plate assumption. By limiting our analysis to two dimensions, we obviously limit our ability to examine the detailed stresses in the weld bead region. We lose very little by this, however, since reliable experimental data in this region are extremely difficult to obtain. By simplifying the bead region, however, and verifying the computed global behavior of the test sample, we can draw some conclusions regarding the gross behavior of the weld bead region.

Our treatment of the weld pool is based upon the following assumptions:

1) The weldment consists of three regions: the molten weld pool, the solidified weld bead and the unmelted material. The temperature at the boundary of the weld pool is known. It is the melting temperature of the welded material. The path of this boundary determines the boundary of the solidified weld bead.

2) The behavior of the molten material does not affect the thermal or mechanical behavior of the unmelted material, other than determining the location of the boundary of the fusion zone. It may actually affect the future behavior of the solidified weld bead, e.g., through constitutive changes, but such changes involve complex metallurgical
details and are not addressed here.

Thus, if one can specify a priori the shape and size of the weld pool, the need to account for the behavior within its boundaries disappears. Since the behavior of the molten material is of no interest with respect to the residual stresses, one need only specify the temperature at the weld pool boundary to completely define the problem. This approach is no less empirical than any other, but it does have two advantages: first, the designer of a particular weld, or the welder himself, should have a good idea of what the size of the weld bead will be. Preliminary analyses could be based upon this knowledge alone. The second advantage is that of simplicity. Separate terms simulating the weld pool behavior are not needed.

Implementing this approach in the finite element analysis is straightforward. In a typical experiment the width of the weld pool averaged 0.6 cm (0.2 in.). Figure 3 shows a finite element mesh that was created with a row of elements whose boundaries correspond to the boundary of the actual fusion zone. The mesh is then welded, one element at a time, by assigning the melting temperature to the fusion zone elements. When the welding arc moves, a new element is assigned the fusion temperature while the previous element cools by conduction to the surrounding material and by convection and radiation to the ambient surroundings.

The thermal and mechanical properties of 304L stainless steel with respect to the temperature were taken from Peckner and Bernstein's Handbook of Stainless Steels (Ref. 17). The plastic behavior was modeled following the algorithm of Krieg, et al. (Ref. 18). Yielding was assumed to occur isotropically, with a slight hardening modulus. Because the boundary of the fusion zone has been assumed a priori, phase change effects have been ignored. Material inside the molten zone, however, was assumed to be strain free, with a reference temperature equal to the melting temperature. Because of the high temperatures associated with welding, radiation from the surface was accounted for. The actual emissivity of the plate will vary not only with the temperature, direction and wavelength, but with the position on the plate (because of surface oxidation) as well. The emissivity of the model was based on a diffuse, gray surface emitting to a black body at room temperature, and was estimated to be 0.5.

**Analytical and Experimental Results**

Figure 4 shows the analytical and experimental temperatures vs. time at var-
ious thermocouple locations. The curves for the thermocouples in Sector 1 show two peaks: the first corresponds to the initiation of the arc adjacent to, and its subsequent movement away from, the thermocouple's location. The second peak corresponds to the approach and subsequent extinguishment of the arc as it completed its travel around the circular path. The set of curves for Sector 2 shows only one peak corresponding to the passage of the arc. Finally, at the center of the plate, a gradual but steady increase in the temperature can be seen as the weld pool circumscribes the inner portion of the plate. The agreement at all other measurement locations was similar to that of the locations shown. The figure demonstrates that, given the dimensions of the weld bead, the global thermal behavior of the sample can be accurately calculated. The major uncertainty in these calculations is the nature of the thermal conditions on the surface of the plate. The agreement in Fig. 4, however, shows that the simple emissivity estimate is adequate.

Figure 5A shows a view of the initial (solid lines) and final (dashed lines) plate configuration based on the movement of the fiducial marks. The welding began at the right edge of Sector 1 and proceeded in the order shown. Note that the view of the deformations depends somewhat on the coordinate system chosen for the measurements. For each set of measurements, i.e., before and after welding, the origin was defined as the center of the plate. Each set of measurements also shared a common axis corresponding to the azimuth at which the welding started. One feature in Fig. 5A is quite apparent: the rigid-body movement of the outer annulus and boss with respect to the inner disk. This can be seen by the variable spacing of the two lines that encompass the bead, and the almost rigid-body shift of the boss with respect to its original position. Figure 5B, which is a view of the analytical deformations, shows the same movements as the experiment.

Figure 6A shows the radial displacement profile along each radial line of fiducial marks. The variable spacing across the weld bead, seen qualitatively in Fig. 5A, can be seen quantitatively as the variation of the slopes of the profiles across the weld bead in Fig. 6A. The rigid-body movement can be seen quantitatively as the spread and pattern of the displacement profiles (from -0.05 to 0.03 cm/-0.02 to 0.01 in.) in the outer radii of the coupon. Figure 6B shows the radial displacement profiles from the analysis. Note that the magnitude,
spread and relative position of the profiles match the experiment.

Figure 7A and 7B shows a comparison of the final residual stresses after welding and cool down. The experimental values are given as a range of stress — the upper value based on purely elastic behavior during the hole drilling process, and the lower value based on elastic-perfectly plastic behavior. The actual stresses, depending on the post-yield behavior of the material, will fall within this range (Refs. 19, 20). The comparison confirms the global behavior calculated in the analysis. It is important to note that while the final deformations are strong functions of position, the final stresses are nearly axisymmetric in nature. Comparisons for plates welded at radii of 2.5 and 5.1 cm were similar. In fact, the overall magnitude of the stresses did not vary with the weld radius.

Finally, Fig. 8 shows the transient total strains for a test in which the weld radius was 2.5 cm. The gauges were located at a radius of 5.1 cm in Sector 1 of the plate. As mentioned earlier, the experimental errors are rather uncertain due to creep in the strain gauge epoxy. The differences between the experimental and analytical values, however, are consistent with this, i.e., epoxy creep will result in a measured value that is lower in magnitude than the actual value. It can also be seen that the analytical and experimental strain paths are qualitatively the same.

Although the welding process is somewhat stochastic and rather complex, the comparisons shown above demonstrate that a relatively simple model can capture the global behavior of the test sample, certainly to within the sensitivity of companion experiments. Using the above examples as a baseline, we can now examine the role that various parameters play in the process. In the following sections we will demonstrate, analytically, the effect of three factors that are commonly encountered in practical welding situations: the application of a heat sink, preheating, and the role that geometry plays in determining the overall constraint of the workpiece.

A Perfect Heat Sink

The assumption behind our "perfect" heat sink is that all heat flowing from the weld bead region into the base metal is captured by a sinking mechanism, allowing the entire plate, except for the weld bead, to remain isothermal. In the analysis, this was modeled by simply ignoring the thermal expansion and temperature dependence of the material properties of the base metal. Although a true heat sink would also affect the temperature history of the weld bead, these assumptions will allow us to observe the effect of the contracting weld bead independently of the thermal expansion of the base metal. Figure 9 shows the resulting radial displacement profiles, while Fig. 10A and 10B shows the radial and hoop stress profiles, respectively. By comparing Fig. 9 to the baseline case shown in Fig. 6B, it can be seen that the deformation within the base metal, the variation in spacing across the weld bead and the spread of the curves in the outer portion of the plate have all been greatly reduced. By comparing Fig. 10A with Fig. 7A, and Fig. 10B with Fig. 7B, a similar reduction can be seen in the stresses throughout the plate.

These comparisons lead to some interesting conclusions. First, it can be seen from the displacements that the contraction of the weld bead itself plays only a minor role in the deformations. The largest factor far by far is the thermal expansion of the base metal and its subsequent restraint. The second conclusion is that the residual stresses can be greatly reduced by keeping the base metal cool, thereby keeping the modulus of elasticity and yield strength as high as possible throughout the process. In this case, the contraction of the weld bead, which was yielding and relatively compliant, was never enough to cause the base metal to yield.

Obviously, this analytical example could never, in reality, be achieved. But it does raise some interesting questions, such as: "How much of a perfect sink can be achieved, and what will be the resulting effect on distortions and stresses?" Another factor that this type of analysis does not address is the metallurgical consequences that are associated with changes in the temperature gradients and cooling rates. Such factors, of course, must be accounted for in practical situations.

A Perfect Preheat

Preheat treatments are used primarily to affect the time at temperature and cooling rates within the weldment in order to obtain a desired microstructure. Another beneficial effect, however, is that the reduction in the range of temperature over which the weldment is cooled causes a reduction in the thermal shrinkage stresses. In this analysis, a preheat was simulated by assuming that the initial, or reference temperature of the plate, was 260°C (500°F). Figure 11A and B shows the radial and hoop stress profiles, respectively. A compari-
son of Fig. 11 with Fig. 7 shows that the overall magnitude of the stresses has been markedly reduced, although not to the extent shown in the case of a perfect heat sink. The magnitude of the deformations, although not shown here, was similarly reduced.

Effects of Geometry

A primary reason for using a circular geometry in this study was a desire to develop a test specimen in which the thermal and mechanical behavior could be readily manipulated through changes in the welding parameters and applied restraints. The heat sink and preheat analyses demonstrate the effect that changes in the welding environment can have on the distortion and residual stresses for a given geometry. The distribution and magnitude of the residual stresses can also be affected, however, by changes in the geometry itself. A variable-restraint test such as this might be desirable, for instance, in order to simulate the range of restraint expected in the welding of a full-scale design or prototype. For these analyses, the degree of restraint in the plate was varied by welding a partial circle, instead of a full-circle bead. A narrow groove was machined into the plate before welding to further reduce the internal restraint on the contracting weld bead — Fig. 1.

Figure 12A shows the final radial stress profiles at the midpoint of the weld bead length (i.e., in the area of highest restraint/residual stress) for specimens with $\frac{1}{4}$-, $\frac{1}{2}$-, $\frac{3}{4}$- and full-circle weld beads. In this case, the restraint transverse to the weld bead increases as the length of the weld bead increases. For the $\frac{3}{4}$-circle bead, the inner portion of the plate is almost completely free to move as the weld bead contracts, the level of restraint (and thus the resulting level of the transverse stresses) is relatively low. On the other hand, the full-circle bead applies the largest restraint, resulting in high transverse stresses. By varying the length of the weld bead, the transverse stresses can be easily manipulated.

Figure 12B shows hoop stress profiles for the same analyses at the same points. These stresses show much less sensitivity to the geometry changes simply because the restraint parallel to the weld bead is relatively independent of the length. In this case, the hoop stresses will be large regardless of the weld bead length.

Conclusions

While the welding process is highly complex, the analytical and experimental comparisons shown here demonstrate that many of its parameters can be characterized by applying some very basic assumptions. In this study, we used the analytical models to examine three idealized variations of a baseline welding procedure: the addition of a heat sink, the use of preheating and changes in the geometry of the weldment. Each of these variations had a quantifiable effect on the distortions and residual stresses predicted by the model. The ability to examine such variations can be useful in several practical situations:

1) The effect of a particular welding parameter may be judged independently of other parameters. This is often impossible to do in actual experiments.

2) The welding procedure could be at least partially determined during the initial design stages of manufacture, where adjustments to unforeseen problems are least expensive.

3) The thermal and mechanical behavior in welding tests can be manipulated in order to judge the performance of the weld under known states of temperature, distortion and stress.

Regarding the scenarios in this study, it was seen that the application of a “perfect” heat sink greatly reduced both the distortions and residual stresses. The use of preheating, while having little effect upon the final distortions, also reduced the residual stresses. Changes in the geometry of the weldment were seen to completely change the magnitude and distribution of the residual stresses. Another major result is the essential difference between the deformation and stress fields and their effects on the desired weld criteria. If final deformations are the measure of a good weld, i.e., preventing interference effects, then the strong circumferential variation must be considered and a fully transient analysis must be performed. On the other hand, if residual stresses are the measure, then a more simple axisymmetric analysis may suffice.

Many of the qualitative trends listed above are already well known. The most important aspect of this study, therefore, is the attempt to quantify the effects associated with process controls that are commonly used in the welding process. Simple models will certainly not explain all of the phenomena that occur in the fusion welding process. On the other hand, this study demonstrates that they can quantify important factors, especially with regard to the gross behavior of the weldment. Just as important is the need to fully investigate the strengths and weaknesses of simple techniques in order to build a solid foundation for later, more complex models.

References

1. Stout, R. D., McGeady, L. J., and Dean, D. E. 1946. Quantitative measurement of the

WRC Bulletin 366
August 1991


Edited by A. K. Dhalla

The recommended practices for elevated temperature design of Liquid Metal Fast Breeder Reactors (LMFBR) has been consolidated into four volumes and is published in four individual WRC Bulletins.

Volume I — Current Status and Future Directions, in WRC Bulletin 362, April 1991
Volume IV — Special Topics, in WRC Bulletin 366, August 1991

In Volume IV, WRC Bulletin 366, special topics such as, fracture mechanics, nonlinear collapse stress classification of structural discontinuity stresses, and high-temperature design as practiced in Germany are discussed. Flaw evaluation (fracture mechanics) procedures are recommended to supplement the design codes which assume perfect, defect-free structures. The fracture mechanics methods have been extended into the plastic and creep regimes.

Publication of this Bulletin was sponsored by the Committee on Elevated Temperature of the Pressure Vessel Research Council. The price of WRC Bulletin 366 is $40.00 per copy, plus $5.00 for U.S. and $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th St., New York, NY 10017.