DETERMINING RESIDUAL STRESS
THROUGH THE THICKNESS OF A WELDED PLATE

Michael R. Hill

Drew V. Nelson

Mechanical Engineering Department
Stanford University
Stanford, California

ABSTRACT

In this paper, we review several destructive methods used to find triaxial residual stress in thick welded plates. The finite element method is then employed to simulate the application of each technique in the context of a model problem. Each technique is discussed in terms of its accuracy and the amount of work required to obtain the estimated residual stress. Finally, a test specimen is proposed, into which a known residual stress field can be introduced, for physical experiments to verify the computations on which this paper is based.

INTRODUCTION

Although measurement of triaxial subsurface residual stress might seem simple in this modern age, there have been relatively few methods presented in the literature to perform such measurements. One method is neutron diffraction, but that requires access to a nuclear reactor. In what follows, we will focus on destructive methods for triaxial residual stress determination. Such methods use tools readily available in most industrial laboratories, so they are often the most practical, although not the most simple. We will review a few of these methods, and then compare them based on numerical simulation.

The little data available in the literature for thick welds suggest that several characteristics of the residual stresses make their determination difficult. Perhaps the foremost challenge with such welds is the presence of high stress gradients with respect to geometry. Also, the residual stress field is always triaxial, with possibly all six components of residual stress being nonzero. Thick welded plates, therefore, present one of the most difficult residual stress distributions to measure.

Perhaps the most frustrating aspect of residual stress for the engineer is that residual stress is altered when a weld is sectioned to allow access for instrumentation. Samples must be removed from a structure in the process of residual stress determination, and these samples must be sectioned into smaller pieces. Assumptions about how residual stresses change when samples and sections are separated must always be made. The validity of these assumptions often determines the accuracy of the method. The change in strain which occurs on the surface of a removed section is usually measured and used to find the preexisting residual stress. The calculation of residual stress from measured strains is referred to as back-calculation by several authors.

METHODS OF RESIDUAL STRESS DETERMINATION

We will review three available methods capable of revealing triaxial residual stress deep within a component. All of these methods were developed to be applied to flat welded plates and they are enumerated below in the order in which they first appeared in the literature. The methods are presented below only in enough detail to allow their comparison. Additional information can be obtained from the original references.

It will be helpful to provide some basic coordinate definitions at this point. A butt welded plate has directions which correspond to the weld bead as shown in Fig. 1. These consist of the transverse, perpendicular, and longitudinal directions relative to the direction of welding. We have chosen corresponding coordinates x, y, and z, respectively.

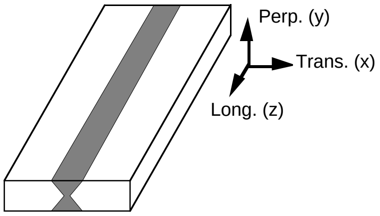

FIG. 1 – DIRECTIONS RELATIVE TO A WELD

Method Proposed by Norton and Rosenthal (1945)

Norton and Rosenthal suggested a method based on removal of two thin slices of material from a thick weld. The location and orientation of these two samples is shown in Fig. 2. One sample lies in the longitudinal-perpendicular plane, and one in the transverse-perpendicular plane. These are referred to as the longitudinal and the transverse samples, respectively.

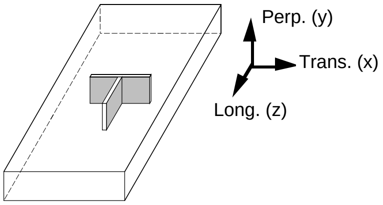

FIG. 2 – TWO SLICES REMOVED IN THE ROSENTHAL-NORTON TECHNIQUE (1945)

Residual stress in the welded plate is known to be the residual stress in each slice added to the residual stress released when the slices are removed from the plate, as follows from superposition.

Norton and Rosenthal estimate the residual stress in each slice assuming that residual stress exists only along the long axis of the slice. They make use of a combination splitting and layer-removal technique to reveal the assumed-uniaxial residual stress field in each slice.

The strain released when the samples are removed from the plate is found based on one simple assumption: the stress released in the long axis of the slice is a linear function of the perpendicular coordinate. Therefore, stress released when the slices are removed from the plate is measured on the top and bottom surfaces of the weld. This is done by installing electrical-resistance strain gages prior to cutting. The stress released at any point through the thickness is then found by linear interpolation.

The initial residual stress in the plate is found by adding the residual stress in the removed samples to the linearly distributed stress released when the samples were removed from the plate.

Method Proposed by Gunnert (1961)

Perhaps the earliest and most complete treatise on measurement of weld residual stress was provided by Gunnert, originally written in Swedish (about 1936) and then translated into English (1955). He presented results of a novel technique to measure triaxial residual stress somewhat later (Gunnert, 1961). This method makes use of pairs of measuring holes and incremental overcoring to release residual stress. Two pairs of small holes are drilled completely through the thickness of the welded plate, one pair lying in the x-y plane, and the other in the y-z plane. For each pair of holes, the center-to-center distance is measured as a function of depth in the perpendicular direction. A core including these holes is removed from the plate, and the distances are measured again. The strain released in each direction is then computed. Residual stress originally in the plate is computed from the measured strain, assuming that the core is stress-free. In Fig. 3 we show a section cut through a measurement site.

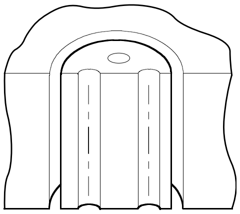

FIG. 3 – SECTION THROUGH A MEASUREMENT POINT WHERE GUNNERT'S TECHNIQUE WAS APPLIED

To include the measurement of perpendicular residual stress, the core is removed in an incremental fashion. Overcoring is done to a specified depth, then the length of the core in the perpendicular direction is measured using a special gage. By measuring this length as a function of overcore depth, strain released can be computed as a function of distance in the perpendicular direction and used to find residual stress.

Two important assumptions are made in Gunnert's method. First it is assumed that the creation of the measuring holes does not alter the initial residual stress field, and second, that the removed core is stress free. Creation of the measuring holes will surely disturb the residual stress field within the region near the holes. If the removed core is large compared with the size and layout of the holes, the stress released by overcoring will not be influenced by the measuring holes. However, if the core removed is to be stress free, then it must be small relative to the spatial variation of the initial residual stress field in the transverse and longitudinal directions. It is widely accepted that the variation of residual stress is small in the longitudinal direction some distance from the ends of a welded plate. However, measurements of residual stress on the top surfaces of welded plates show that the variation in the transverse direction is large, except very close to the middle of the bead. In selecting measuring hole and overcore dimensions, these competing factors must be carefully balanced.

Despite these difficulties, Gunnert's work represents the most complete results provided by a direct strain relaxation based experimental method. More involved sectioning techniques, such as that suggested by Rybicki and Shadley (1986), make use of more complex and less obvious assumptions than those called for in Gunnert's technique. For this reason, it may be reasonable to assume that the Gunnert technique provides at least a good approximation to the residual stress field present in welded plates. In that spirit, we present Gunnert's results for residual stress at the center of the bead and middle of the weld-length as a function of distance through the thickness for a double-sided butt welded plate. These are shown in Fig. 4. We take these results to be representative of the basic character of weld residual stress at this location in such a joint.

Gunnert's technique was updated by Procter and Beaney (1987). Their procedure uses only one measuring hole, the diameter of which is measured in three directions, before and after overcoring, with a special transducer. This method is depicted in their paper as shown in Fig. 5. The use of a single hole allows the removed core to be smaller, improving accuracy in regions of residual stress gradients. The length of the core in the perpendicular direction is measured during overcoring with an LVDT and is used to find the perpendicular residual

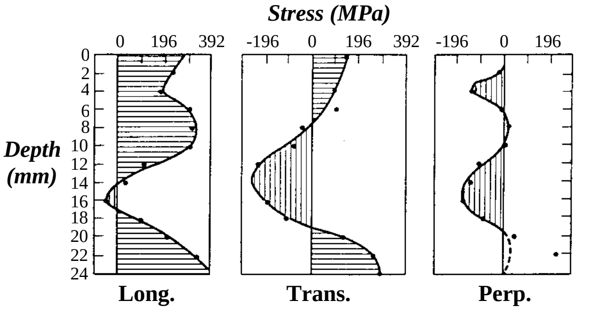

FIG. 4 – RESIDUAL STRESSES REPORTED BY GUNNERT (1961)

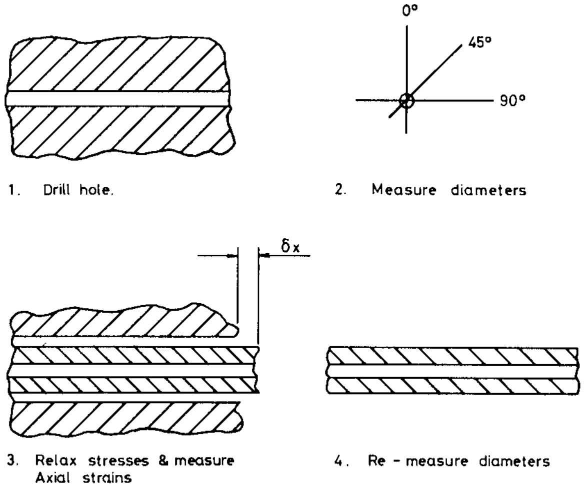

FIG. 5 – SCHEMATIC OF THE TECHNIQUE PRESENTED BY PROCTER AND BEANEY (1987)

stress. Their method uses a back-calculation routine derived from finite element simulations to find residual stress from the measured displacements. When compared with Gunnert's technique, the method requires a greater diameter-measurement accuracy for the same accuracy in released strain and residual stress since the effective gage length for measured strain is reduced. To execute these high-accuracy measurements, Procter and Beaney developed a special, high-sensitivity transducer.

Method Proposed by Ueda (1975)

Ueda has proposed a general method for determining triaxial residual stress. His technique for a welded plate is based on the more general "Inherent Strain Method". The differentiating characteristic of this class of procedures is that residual stress is found through estimation of the *source of residual stress* within the weld. Experts on continuum mechanics and elasticity, including Timoshenko (1970) and Mura (1987), acknowledge that residual stress is the result of some inelastic strain field which does not satisfy compatibility. This strain field is present because of mechanical and thermal processes which the body has undergone. Ueda refers to the inelastic, non-compatible strain as "inherent strain", while we will adopt Mura's terminology by calling it "eigenstrain". For a welded joint, the eigenstrain field is the combination of thermal, transformation, and plastic strains which are the net result of the welding process.

Although residual stress is caused by eigenstrain, it is also a function of the geometry of the body. A long weld and a short weld can possess the same eigenstrain distribution while having a different residual stress. For example, imagine a welded plate which is 1 m in length. If a sample of this plate is produced by removing the middle 50 mm along the weld-length, stress will be released in removing the sample. The stress has changed, but the eigenstrain within the removed sample remains the same. (We assume that cutting out the sample produces no new plastic strains. The cutting process is assumed to be elastic.) The inherent strain method is a form of destructive sectioning, as strain released during geometry changes is used to deduce the underlying eigenstrain distribution.

The exact technique reviewed here was presented by Ueda (1985) for use on continuously welded joints and further studied in a recent paper (Hill, 1995). The assumption of continuous welding allows Ueda to consider an eigenstrain field that is dependent on the transverse and perpendicular coordinates, while independent of the longitudinal coordinate. The basis for this assumption is that each plane in the weld cross-section is thought to experience the same thermal and mechanical processes during welding. Two such planes are shown in Fig. 6. Clearly this assumption does not hold in either the thermal or mechanical sense near the ends of the joint, as noted by Ueda.

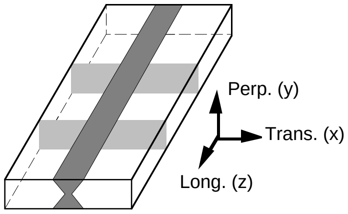

FIG. 6 – TWO PLANES WHICH HAVE THE SAME EIGENSTRAIN DISTRIBUTION

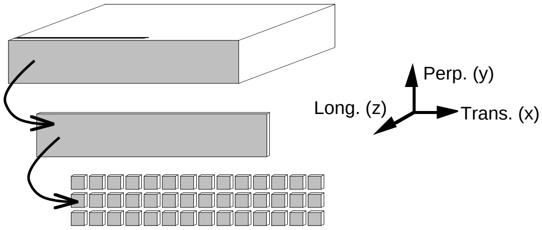

FIG. 7 – PICTORIAL REPRESENTATION OF THE SLICE-AND-DICE METHOD PROPOSED BY UEDA (1985)

An illustration of Ueda's technique is shown in Fig. 7. A sample of a welded plate is obtained from the structure of interest and an array of strain gages is attached to one of the sample's longitudinal faces (shown shaded in the figure). Two strain-relaxation measurements are then performed, one from block to thin slice and the other from slice to small pieces (dice), each containing a strain gage. The slice-to-dice data allow determination of the eigenstrain components in the transverse-perpendicular plane. Using these results with the block-to-slice relaxation data allows determination of the eigenstrain component associated with the longitudinal direction. The determination of eigenstrain components from measured strain changes involves solution of a linear system found by repetitive finite element method calculations, as described by Hill (1995).

NUMERICAL APPLICATION OF THE METHODS

The accuracy of the three methods described above will depend greatly on the residual stress distribution being measured. Our goal in this section is to state the accuracy with respect to one residual stress system in particular.

We will investigate in detail the methods proposed by Norton and Rosenthal and by Ueda. The method proposed by Gunnert will not be simulated here as Procter and Beaney have already executed a similar study of their Gunnert-like technique. Their results show that the method is able to capture the residual stress distribution with good accuracy (Procter, 1987). However, their simulations address neither the sensitivity of the method to variations of residual stress in the transverse and longitudinal directions nor the influence of the measuring hole on the relaxed stress.

Baseline residual stress state

Residual stress is to be determined within a sample of welded plate shown in Fig. 8. The residual stress field present in this sample is one which resembles both the results of Gunnert, shown in Fig. 4, and the well known characteristics of residual stress on the surface of thick welded plates. Residual stress is shown in Fig. 9 and Fig. 10 along contours within the x–y (transverse-perpendicular) plane at the middle of the sample with respect to the weld direction. These plots serve to demonstrate the character of this sample residual stress field. These stresses are the result of a finite element computation and are identified as “exact”, meaning that a perfect measuring technique would obtain the same results.

Residual stress is produced in a finite element model of the specimen shown in Fig. 8 by introduction of an eigenstrain field. The resulting residual stress state is fully three-dimensional, and exists everywhere within the body. The specific eigenstrain field used is given in detail in an earlier paper (Hill, 1995). This field was developed to produce a complicated residual stress field that *resembles* the character of thick-weld residual stress; however, this field should not be construed to *be* the residual stress state present in any real weld. Its sole purpose is to provide a basis by which to compare techniques for residual stress determination.

Technique used to compare the methods

To simulate a measurement technique using the finite element method, we analyze each sample and section removed using three-dimensional finite element models. Stress in each piece is due to the eigenstrain field, which is known since we assume that the cutting process causes no new eigenstrain (i.e., plastic deformation) in the removed pieces. The stress change due to removal of a sample is determined by subtraction of the stress in the sectioned configuration from the stress in the original configuration. We “measure” the stress and strain changes by taking nodal results from the computation. In this way, no effort is made to account for the finite size of the strain gages which would be used in the corresponding physical experiments.

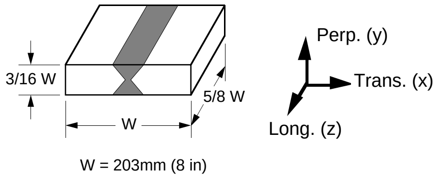

FIG. 8 – SAMPLE IN WHICH RESIDUAL STRESS IS TO BE DETERMINED

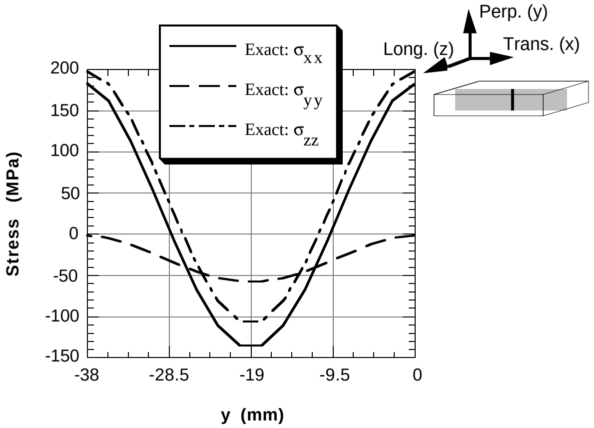

FIG. 9 – RESIDUAL STRESSES AT THE CENTER OF THE SAMPLE, THROUGH THE THICKNESS OF THE PLATE

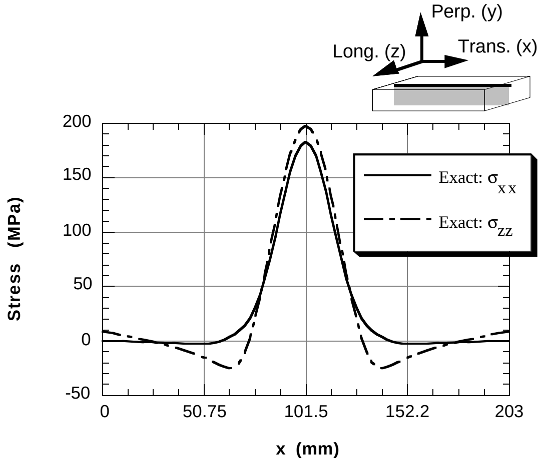

FIG. 10 – RESIDUAL STRESS AT THE CENTER OF THE WELD LENGTH, ACROSS THE TOP SURFACE

Simulation of the Rosenthal and Norton Method

Simulation of the Rosenthal-Norton method requires three finite element models. The first model is of the sample shown in Fig. 8, the second and third models correspond to the two specimens shaded in Fig. 2. These two slices both measure 76 mm long, 38 mm wide, and 6.5 mm thick. Stress released when these two slices are removed from the plate is found at the mid-length of each slice at points corresponding to the top and bottom surfaces of the original welded sample.

It is not our goal here to review the determination of the supposedly uniaxial residual stress which is present in these thin slices. This subject has been summarized in several places, including the SAE handbook on residual stress determination (SAE, 1965). It is noteworthy, however, that the uniform uniaxial assumption made by Rosenthal and Norton can lead to large errors when applying the layer-removal technique to the transverse slice (Cheng, 1986).

We will assume that the stress along the axis of the slice is measured with perfect accuracy and address the aspects of the method related to the triaxial nature of the technique. This amounts to checking the linear-stress-release assumption.

Simulation of Ueda’s Method

Simulation of Ueda’s method requires two finite element models, one of the block shown in Fig. 8 and one of a 6.5 mm thick slice removed from the x–y free surface of the block, as shown in Fig. 7. A measuring grid is set up on the block face such that most dice cut from the slice measure 10.2 mm by 6.5 mm, x by y. Dice cut from the top and bottom of the slice, with respect to the perpendicular direction, are smaller, 10.2 mm by 3.2 mm.

We do not model the dicing of the block, since we wish to focus on the three-dimensional aspects of the method. As was done in simulating the Rosenthal-Norton technique, we assume that residual stress in the slice is measured exactly. In this method, however, the measured stress field is not uniaxial and all three components of the planar stress field are measured.

RESULTS AND COMPARISON OF THE METHODS

Residual stress present in the two Rosenthal-Norton slices is shown in Fig. 11 and Fig. 12, together with that in the welded sample. The stress released in the sectioning process is the difference between the stress in the two geometries, and is also shown in the figures. It is clear from these plots that the released stress is far from a linear function of the perpendicular coordinate. Accordingly, the estimated residual stress in the block is inaccurate as shown in Fig. 13. The accuracy is so poor in fact as to preclude the use of the method altogether. It is true that the method gives good results near the surface, but many other options exist to obtain near-surface results.

Ueda’s method, on the other hand, gives much less error in stress, as shown in Fig. 14. This method has little error, except in the longitudinal component of residual stress near the mid-thickness of the block. The success of the method is due to the suitability of its basic assumption: residual stress in the block is caused by an eigenstrain field which *is* independent of the longitudinal coordinate.

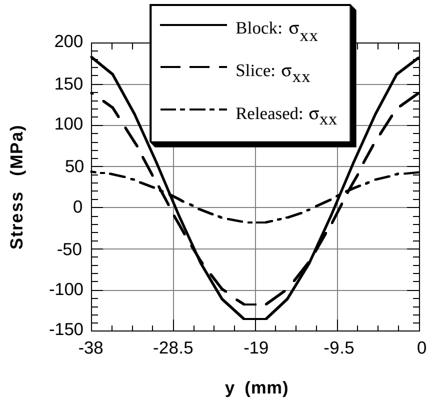

FIG. 11 – STRESS RELEASED AT THE MIDDLE OF THE LENGTH OF THE TRANSVERSE SLICE

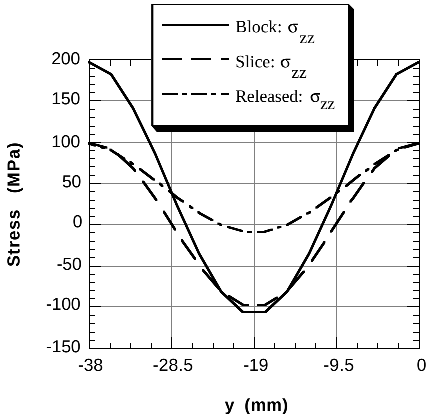

FIG. 12 – STRESS RELEASED AT THE MIDDLE OF THE LENGTH OF THE LONGITUDINAL SLICE

The following physical experiment was conducted to investigate the independence of eigenstrain in the longitudinal coordinate in a long continuous weld. A weld was made by submerged arc welding 38 mm thick pressure vessel steel to produce a welded sample 710 mm long and 203 mm wide. A longitudinal slice was removed from the center of this weld in exactly the way as would be done in executing the Rosenthal-Norton method (Fig. 2). This slice was 203 mm long, 6.5 mm thick, and 42.2 mm wide (the additional width due to overfill of the welded joint). Strain gages were attached to the specimen and the slice sectioned as shown in Fig. 15.

Results show that the strain released during sectioning was independent of the location along the sample as shown in Fig. 16. This indicates that the residual stress and, therefore, the eigenstrain field causing it is independent of position along the sample. It can then be surmised that in this weld, the eigenstrain distribution is independent of the longitudinal coordinate. Whether this is true in most cases, or

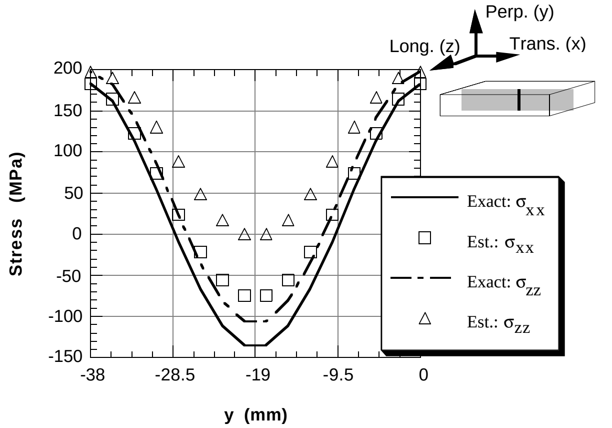

FIG. 13 – RESULTS OF THE ROSENTHAL-NORTON TECHNIQUE AT THE MIDDLE OF THE WELDED BLOCK

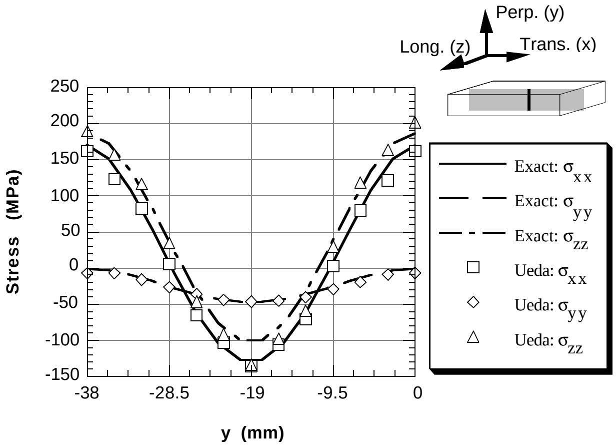

FIG. 14 – RESULTS OF UEDA'S METHOD AT THE MIDDLE OF THE BLOCK COMPARED WITH TRUE VALUES

how this method will perform when the assumption is not valid is a subject for further study. These experiments indicate that this assumption is valid for the one continuously welded joint examined.

As described in the original paper, the Rosenthal-Norton technique gives results only where slices of material are removed from the plate. The complete state of stress is determined by interpolation of the results from one slice removal location to another. In this example, having removed two slices, stress is fully determined at the center of the block as a function of perpendicular distance from the top surface to the bottom.

The method proposed by Ueda, on the other hand, estimates the residual stress state in the entire body. We have shown results at the center of the joint, through the thickness, but similar plots may be made with respect to any line through the body. For example, stress is plotted in Fig. 17 along the same line as in Fig. 10.

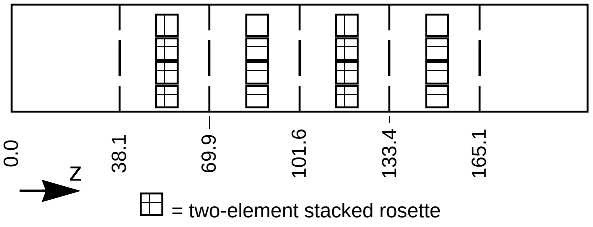

FIG. 15 – GAGE LAYOUT AND CUTTING LINES FOR EXPERIMENT ON EIGENSTRAIN DISTRIBUTION

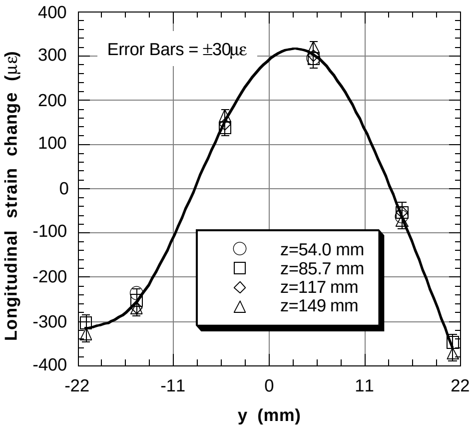

FIG. 16 – STRAIN CHANGE AT VARIOUS POINTS ALONG THE LENGTH OF A LONGITUDINAL SLICE REMOVED FROM A WELD

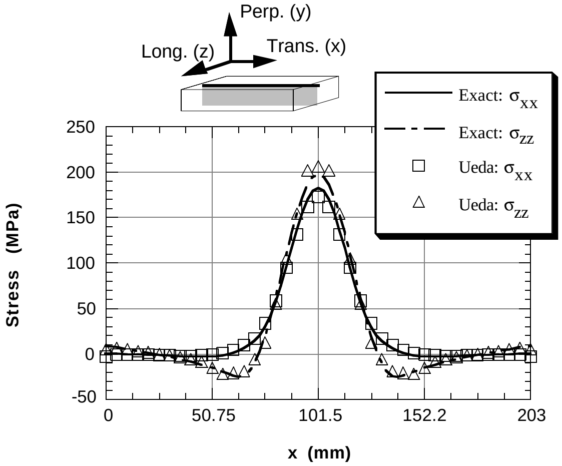

FIG. 17 – RESULTS OF UEDA'S METHOD AT THE CENTER OF THE WELD LENGTH, ACROSS THE TOP SURFACE

The additional information provided by Ueda's method does not come for free. The physical experiment corresponding to the numerical one summarized here would require use of 140 three-element strain gage rosettes, each being measured a minimum of three times. Execution of this method requires a large amount of work, especially when compared to the simpler method advanced by Gunnert.

The Gunnert technique described earlier appears to produce fairly accurate results, according to Procter and Beaney (1987). The method seems fairly easy to execute given the proper tools and measuring devices. One drawback, however, is that results are obtained only in the region of the overcore. As such, the whole residual stress field cannot be measured as it can be with Ueda's method. Nevertheless, the method is quite valuable if subsurface stresses are needed in only one spot.

TESTING TO VERIFY NUMERICAL RESULTS

Several conclusions have been drawn above based solely on numerical modeling and investigation of one particular residual stress field. Most engineers would agree that while such evidence is valuable, some sort of physical evidence is needed to judge one method superior to another. One possible way to perform such a comparison is to find a combination of specimen geometry and mechanical process by which a known residual stress field can be introduced.

This has been done in the past to evaluate other residual stress measurement methods. Two-dimensional residual stress measurement techniques have been evaluated using the cold-bent bar, for example. Similarly, autofrettaged tubes have been applied to evaluate axisymmetric methods. These two types of specimens contain a residual stress state which is either easily measured or can be obtained with good accuracy by direct calculation. Experimental results are then compared with the available theoretical or known solution. For a general triaxial residual stress field, it is difficult to invent such a specimen.

Since welding is the most common source of triaxial residual stress, it is tempting to use it as a verification tool. However, despite the advances made in weld-mechanics, the residual stress state imposed by a given welding process remains unknown. Something more simple and more predictable is needed to verify these methods.

Our thought is to make use of the autofrettage process, since it is deformation-based. The ability to model this process requires a nonlinear finite element code and a knowledge of the room temperature constitutive behavior of the material of interest. This is clearly much simpler than attempting to model the weld process, with temperature dependent material properties, weld-pool turbulence, and transformation strain, among other complications.

A sketch of a proposed benchmark specimen is shown in Fig. 18. The overall dimensions of this specimen would be similar to those of the block shown in Fig. 8. Holes drilled through the length of the specimen would be autofrettaged, setting up a triaxial residual stress state in the region between the holes. These holes would only make the task of finding residual stress marginally more difficult. The boundary of the hole can be handled mathematically in a similar manner to an eigenstrain field. Accordingly, the ability to include the influence of the holes should not be a great leap.

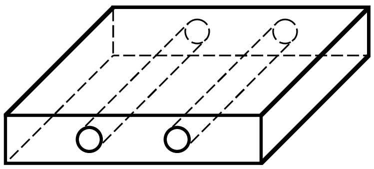

FIG. 18 – SPECIMEN PROPOSED FOR BENCHMARK TESTING OF RESIDUAL STRESS DETERMINATION TECHNIQUES

CONCLUSIONS

In the above we have investigated three triaxial residual stress measurement techniques intended for application to welded joints. Based on computational simulation of these techniques the following conclusions can be drawn.

1) The method proposed by Rosenthal and Norton is subject to large errors in estimated stress. These errors result from an overly simplistic assumption regarding stress released when samples are removed from the welded plate.

2) The overcoring method proposed by Gunnert and further refined by Procter and Beaney is useful for the determination of residual stress at one location, through the thickness of the joint. The method appears to be free of overly-simplistic assumptions about the underlying residual stress state, and was shown to produce good results by Procter and Beaney.

3) The method proposed by Ueda allows determination of residual stress throughout the entire welded joint when the eigenstrain field is independent of the longitudinal coordinate. The method produced good results when this assumption was valid.

4) Experimental evidence indicates that the eigenstrain distribution in long continuously welded joints may indeed be independent of the longitudinal coordinate.

5) There is need for a triaxial residual stress specimen which would allow comparison of these and other techniques on the basis of physical experiments.

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