| Title | Prediction and Control of Residual Stresses and Distortion in Welded Structures |
|---|---|
| Author(s) | Masubuchi, Koichi |
| Citation | Transactions of JWRI. 1996, 25(2), p. 53-67 |
| Version Type | VoR |
| URL | https://doi.org/10.18910/9884 |
| rights | |
| Note | |

Trans. JWRI, Vol. 25(1996), No.2

# Prediction and Control of Residual Stresses and Distortion in Welded Structures

**by Koichi Masubuchi**

Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

## Abstract

*This paper first discusses fundamental characteristics of residual stresses and distortion in welds and development for techniques analyzing them. A major problem that makes the analysis and control of distortion produced by arc welding very complex is that two separate parts are joined to become one piece by heating with a moving heat source. Then presented are experimental and analytical results generated recently at MIT on transient metal movement during welding some simple weldments. Based on these results, classification of metal movements due to welding is discussed. The author then makes comments on the present state-of-the-art of theoretical prediction of residual stresses and distortion in welds and possible applications of theoretical prediction capabilities for solving various practical problems.*

## 1. Introduction

It is my great pleasure to present this paper at the Intentional Symposium on "Theoretical Prediction in Joining and Welding." I am especially pleased to have the opportunity at this time, because I received my bachelor's degree in naval architecture from the University of Tokyo in September 1946, slightly over 50 years ago. In 1947 when I was a graduate student, the United States government sent a mission to Japan to evaluate the state of the shipbuilding technology. The mission included Mr. H. Pierce, Vice Chairman of the New York Shipbuilding Corporation, who also became President of the American Welding Society. The conclusion of the mission was that the Japanese shipbuilding technology was as advanced as that of advanced nations in most fields except welding technology. The mission even predicted that it would take approximately 25 years for Japan to catch up with other advanced nations in welding technology. After hearing this conclusion, the Japanese government embarked on a crash program on welding research. After almost 50 years, I am very pleased that Japanese welding technology is one of the most advanced in the world. I hope that this tradition will continue into the 21st century"

The technologies related to welding may be classified into two sections:

(1) Materials joining technology concerned with joining two pieces of materials together.

(2) Welding fabrication technology concerned with fabricating complex structures including ships, railway cars, space structures, and pressure vessels, using the materials joining technology.

My involvement has been primarily on the welding fabrication technology. Although I have been involved in basic research throughout my professional life, I have always been interested in how to apply results of the basic research for advancing the technology of welding fabrication of complex, critical structures.

Because a weldment is locally heated by the

---

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka567, Japan.

welding heat source, its temperature distribution is not uniform and changes as welding progresses. During the welding cycle, complex strains occur in the weld metal and the base-metal regions near the weld. The strains produced are accompanied by plastic upsetting. As a result, residual stresses remain after welding is completed, and shrinkage and distortion are also produced. Correcting unacceptable weld distortion is extremely costly and in some cases impossible. In addition, excessive shrinkage and distortion cause mismatch of joints thus increasing the possibility that welding defects will occur. Excessive lateral distortion decreases buckling strength of structural members that are subjected to compressive loading. Thus, the development of proper techniques for reducing and controlling distortion would lead to more reliable welded structures with a reduction in fabrication cost. As the technology advances, we will design and fabricate various types of critical structures with improved performance such as higher travel speed and deeper diving capabilities. Many of these structures require increasingly stringent requirements for controlling residual stresses and distortion.

When I think about the progress that has been made on the technology of theoretical prediction of residual stresses and distortion in welded structures, I must say that I have mixed feelings. I am very pleased that by use of modem computers and such techniques as the finite element method we can analyze many cases that were not possible until around 1960. However, we are still far short of successfully using analytical techniques for controlling residual stresses and distortion in actual complex structures. Although it is not possible to discuss many related subjects in this short paper, 1 would like to discuss some important subjects. This paper is composed of the following sections:

(1)Fundamental characteristics of residual stresses and distortion in welds and development of technologies for analyzing them
(2)Results on transient metal movement during welding of some simple specimens
(3)Classification of metal movements and applicability of current analytical techniques
(4)Comments on the present state-of-the-art of theoretical prediction of residual stresses and distortion in welds
(5)Possible applications of theoretical prediction capabilities for solving practical problems.

## 2. Fundamental Characteristic of Residual Stresses and Distortion in Welds and Development of Technologies for Analyzing Them

First, I would like to briefly examine phenomena involved in residual stresses and distortion in welds and how technologies for dealing with these subjects have developed.

### 2. 1 Transient Thermal Stresses Produced by Welding

**Figure 1** shows schematically the changes of temperature and resulting stresses that occur during welding[1]. A bead-on-plate weld is being made along the x-axis. The welding arc which is moving at a speed, v, is presently located at the origin, O, as shown in Figure la. Figure lb shows temperature distributions along several cross sections including:

Section A-A which is ahead of the welding arc
Section B-B which crosses the welding arc
Section C-C which is some distance behind the welding arc
Section D-D which is far behind the welding heat source.

Figure lc shows distributions of stresses along these sections in the x-direction, $\sigma_x$,Stresses in the y-direction, $\sigma_y$, and shear stresses, $\tau_{xy}$ , also exist in a two-dimensional stress field. Along Section A-A, thermal stresses caused by the welding are almost zero. The stress distribution along Section B-B is shown in the figure second from the top. Because the molten metal does not support a load, stresses underneath the welding arc are close to zero. Stresses in regions a short distance from the arc are compressive, because the expansion of these areas is restrained by the surrounding metal where the temperatures are lower. Along Section c-c, as the weld metal and the base metal region near the weld cool, they contract creating tensile stresses in regions near the weld. The right bottom figure shows the stress distributions along Section D-D.

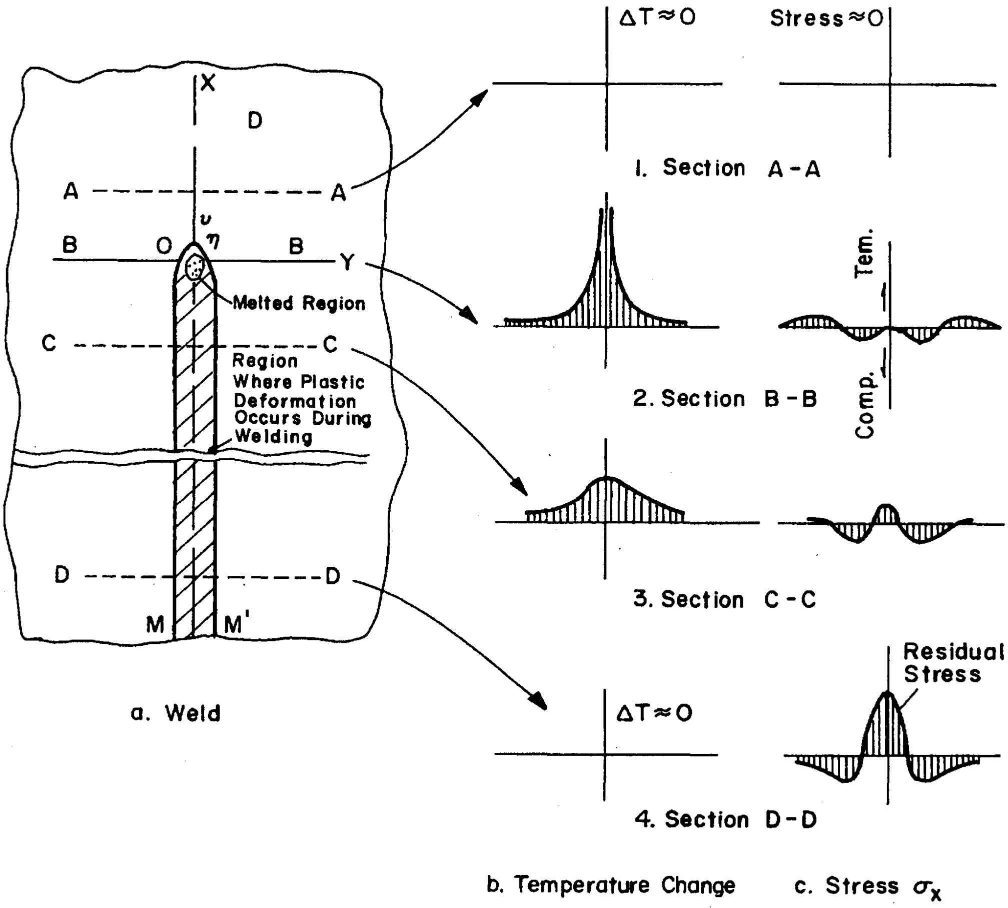


Figure 1 Schematic representation of changes of temperatures and thermal stresses during beadon–plate welding [1].

The cross-hatched region MM' in Figure 1a shows the region where plastic deformation occurs during the welding thermal cycle.

Studies on transient thermal stresses during welding started in the 1930's[1]. However, because of the complex computation required, analyses performed until the late 1950's were limited to very simple cases such as plug welding in which temperature and stress changes are axially symmetric. A breakthrough occurred in the early 1960's when modem computers became available. In 1961, Tall, in his Ph. D. thesis at Lehigh University, developed a simple program on thermal stresses during bead-on-plate welding along the center line of a strip. The temperature distribution was treated as two-dimensional. However, in analyzing stresses it was assumed that: (a) longitudinal stress $\sigma_x$ is a function of the lateral distance y only, and (b) $\sigma_y$ and $\tau_{xy}$ are zero. I call this analysis the one-dimensional program.

Our research group at Battelle Memorial Institute received a contract from the National Aeronautics and Space Administration (NASA) to perform basic research on residual stresses, and a FORTRAN program was developed on the one-dimensional analysis of thermal stresses during welding. The work continued after I moved to MIT in 1968, and we developed a series of computer programs (one dimensional, two dimensional finite-element, and three dimensional finite-element) dealing with transient thermal stresses during welding. At the same time, our group performed a series of experiments on various materials to verify analytical results[1]. Today, many universities and research laboratories in various countries have computer programs on heat flow, residual stresses, and distortion in weldments. The research group under Professor Ueda of the Osaka University has been very active on this subject.

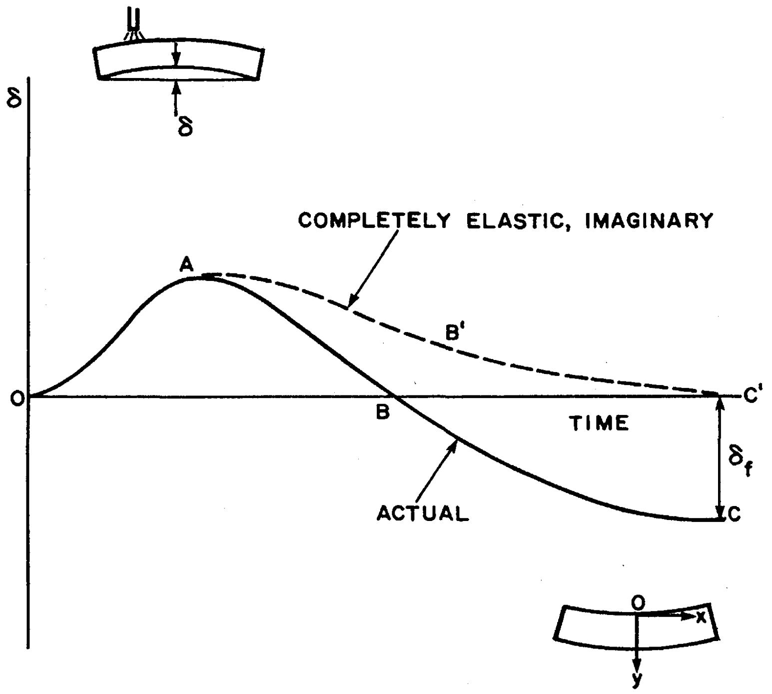


Figure 2 Transient deformation of a rectangular plate during and after welding along the upper edge of a rectangular plate [2,3].

## 2.2 Transient Metal Movement During Welding

**Figure 2** shows schematically how a rectangular plate deforms when arc welding is performed along the upper longitudinal edge[2,3]. Since temperatures are higher in regions near the upper edge, these regions expand more than those near the lower edge causing upward movement of the center of the plate, $\delta$, as shown by Curve OA in Figure 2. When welding is completed and the metal starts to cool, the plate will deform in the opposite direction. If the material were completely elastic in the entire region of the plate during the entire period of the heating and cooling cycle, the plate would deform as shown by Curve AB'C' returning to its original shape with no residual distortion. However, this does not happen in welding a real material, be it steel, aluminum, or titanium. In the case of welding a real material, plastic deformations occur in regions near the upper edge while temperatures are high and yield stresses of the material are low. As a result of the compressive plastic strains (shrinkage) that are produced in regions near the upper edge, the plate continues to deform after passing its original shape (or the horizontal line) resulting in the negative final distortion, $\delta_f$, when the plate cools to its initial temperature (see Curve OABC).

## 2.3 Weld Distortion

In welding fabrication, welding is performed on various types of joints including butt joints, T-joints, lap joints, etc. As a result various types of distortion are produced, as shown in **Figure 3**. Even a simple butt weld, for example, can cause transverse shrinkage, longitudinal shrinkage, angular distortion, and buckling distortion (when large thin plates are welded). Distortion of a complex welded structure is extremely complex. The amount of distortion is affected by many parameters including joint design, welding processes, and welding conditions including welding current, arc voltage, and arc travel speed. The amount of distortion is also affected by various fabrication procedures including joint restraint, welding sequence, etc.

A major problem that makes the analysis and control of distortion produced by arc welding very complex is that two separate parts are joined to become one piece by heating with a moving heat source. This subject is discussed in more

(a) TRANSVERSE SHRINKAGE

(b) ANGULAR CHANGE

(c) ROTATIONAL DISTORTION

(d) LONGITUDINAL SHRINKAGE

(e) LONGITUDINAL BENDING DISTORTION

(f) BUCKLING DISTORTION

Figure 3 Various types of weld distortion [1].

detail in a later part of this paper. The parts being joined make complex movements while joining is being accomplished. Whether or not the parts are restrained has significant effects on the transient metal movement and the final distortion. As the weld metal solidifies, the joint moves as a single body as the temperature decreases. Therefore, in the analysis and control of distortion, it is extremely important to understand mechanisms of transient metal movement and the final distortion. In the case of multipass welding of a butt joint, for example, metal movement during the first pass and those during subsequent passes can be very different.

## 3. Results on Transient Metal Movement During Welding of Some Simple Specimens

Now I would like to present some experimental and analytical results on metal movement during welding on some simple specimens. A series of experiments were performed at MIT for studying transient movements of several types of welds as follows:

(1) Stainless steel plates heated by a stationary gas tungsten arc

(2) Restrained beam models in steel

(3) Out-of-plane movements during butt welding of steel plates

Metal movement during and after heating was measured by laser displacement sensors. The welding research group at the Department of Ocean Engineering at MIT has been using laser displacement sensors developed by Keyence Corp. Osaka, Japan$^{5)}$. **Figure 4** illustrates how the sensor operates. The main feature of the Model LB-08 1 used in these experiments are given in **Table 1**. The sensors were interfaced with a microprocessor. The resolution of the system was approximately 8 μ m. Regarding its response frequency, it can be used as fast as 36 Hz (36 measurements per second), but most measurements were performed at 10 Hz. UP to 6 channels could be used to collect the data from laser sensors.

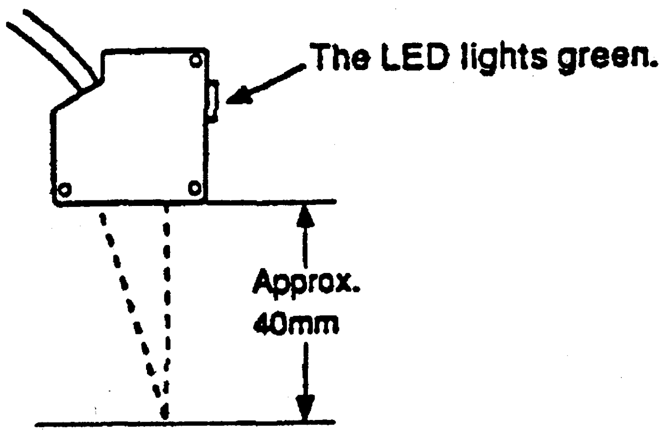


Figure 4 Keyence laser displacement sensor [2,5].

Table 1 Main features of the laser displacement sensor [2,5].

| | | |
|---|---|---|
| Maker | | KEYENCE Corporation |
| Model | Sensor Head | LB-081 |
| | Controller | LB-1101 |
| Light Source | | Semi-conductor Laser<br>Wave Length : 780 mm |
| Reference Distance | | 80 mm |
| Measuring Range | | ± 15 mm |
| Linearity | | 0.25% of F.S. |
| Resolution | | 8 μm |
| Response Frequency | | 36 Hz |

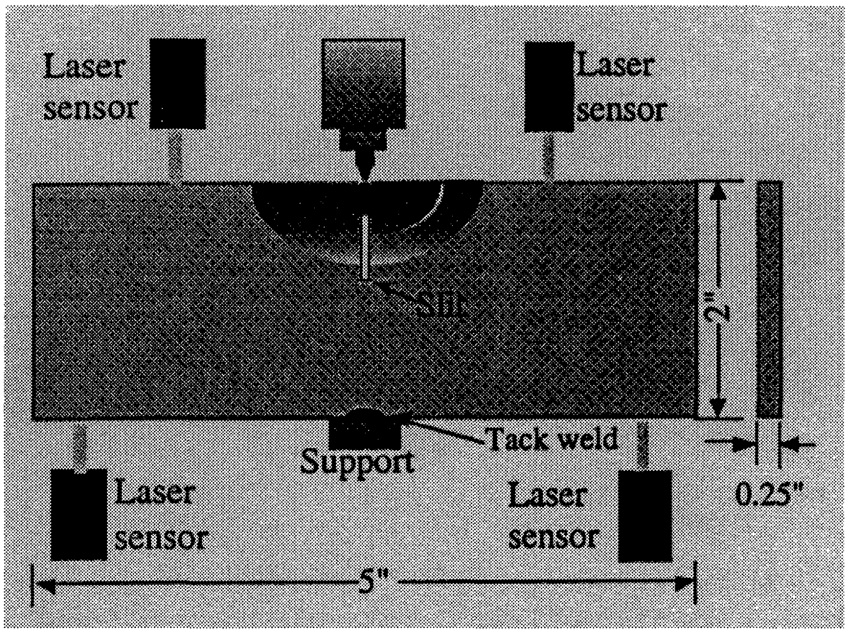


Figure 5 Plate model showing three different configurations :

## 3.1 Transient Movement of Plates Due to Heating by a Stationary Gas Tungsten Arc

**Figure 5** shows the experimental setup[2, 4, 6]. A 304 stainless steel plate 5 inches (12.5mm) long, 2 inches (50 mm) wide and 0.25 inch (4mm) thick, was heated by a stationary gas tungsten arc at the center of the upper edge. The metal movement during and after welding was measured by laser displacement sensors. The specimens were prepared in three different types:

Specimen 1-1: A solid plate

Specimen 1-2: A solid plate with a slit 5/8 inches (15.9 mm) deep in the plate center

Specimen 1-3: Two separate plates 2.5 x2.5x 0.25 in. (63.5 X 63.5X 6.35mm) without tack welds, not restrained.

Each specimen was heated by placing a small weld metal by gas tungsten arc welding with the following conditions:

Polarity d.c. straight polarity (electrode minus)

| | |
|---|---|
| Welding current | 150 Amperes |
| Arc voltage | 13 volts |
| Shielding gas | Argon |
| Welding time | 5 to 6 seconds (manual control). |

For each specimen, transient displacements due to welding were measured at four locations during and after welding. Temperature changes were measured by thermo-couples attached to various locations of the specimens.

**Figure 6** shows results obtained on the solid specimen (Specimen 1-1). Shown here are data obtained on a laser displacement sensor located on the upper edge at a distance 20 mm away from the plate edge or 43.5 mm away from the arc. The tendency of the metal movement observed is the same as predicted by Curve OABC in Figure 2 (upside down). Regions immediately below the arc want to expand, but the expansions are prohibited by the surrounding regions heated to lower temperatures causing compressive plastic strains in regions near the arc. These compressive strains are the cause of the distortion that remains after the specimen cooled down to room temperature. Note that the amounts of metal movement are very small and rather rapid especially during welding. The amount of maximum metal movement observed on this specimen was only about 0.07 mm, and the welding time was only 5 seconds.

**Figure 7** shows similar results obtained on the specimen with a slit (Specimen 1-2). The metal movement was less than that obtained on Specimen 1-1. Since a slit existed below the arc compressive strains produced in regions near the weld were less. Nevertheless, the general trends observed on these two specimens were similar.

**Figure 8** shows results obtained during welding two separate plates (Specimen 1-3). Since two plates were separated, the plates moved as independent solid bodies in large amounts before they were joined when the weld metal solidified. The final distortion was almost 1 mm which is almost 18 times that of the final distortion observed on Specimens 1-1 and 1-2. It is interesting to note that metal movements after welding arc extinguished were similar to all specimens tested including Specimens 1-1, 1-2, and 1-3.

**Figure 9** compares predicted transient temperature history with experimental results obtained on Specimen 1-1. Comparisons are made at three locations, 15, 20, and 30 mm away from the arc along the upper edge of the specimen. The finite element analyses were made using finite element programs developed by Professor Bathe of the Department of Mechanical Engineering, MIT. ADINAT was used for analyzing heat flow, while ADINA was used for analyzing stresses and distortion.

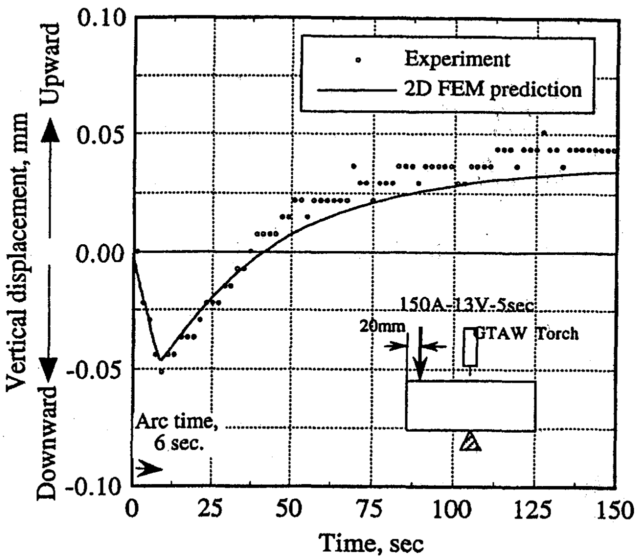


Figure 6 Transient deformation of a solid plate (Specimen 1−1) during and after welding.

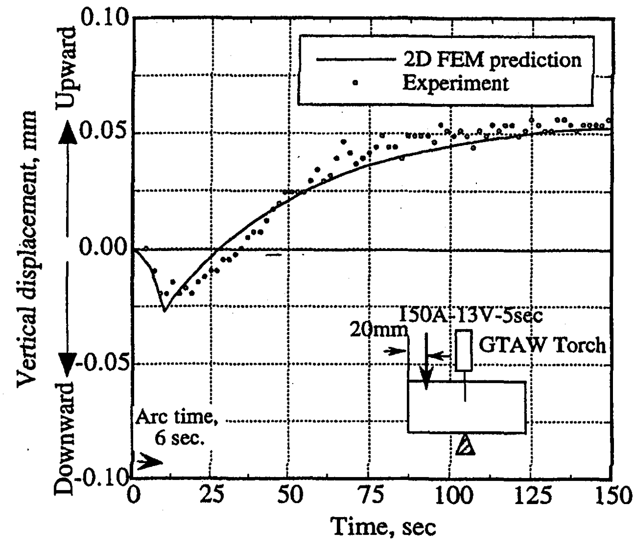


Figure 7 Transient deformation of a plate with a slit (Specimen 1−2) during and after welding.

**Figure 10** shows the FEM mesh used by Goktug in the analysis of heat flow and transient metal movement of stainless steel plates heated

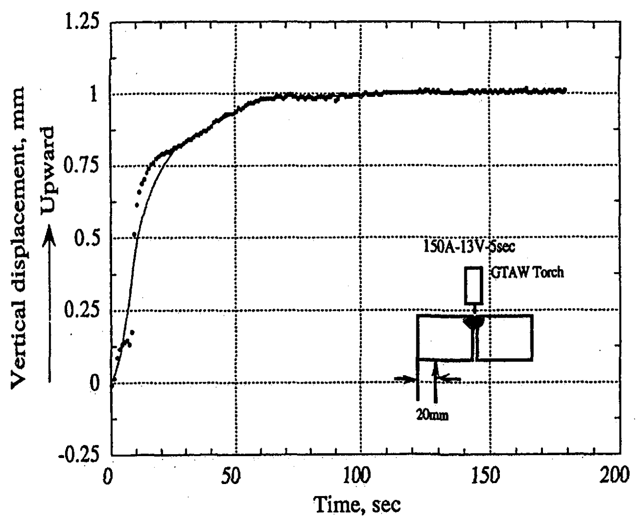


Figure 8 Transient metal movement of two separate plates(Specimen 1−3)during and after welding.

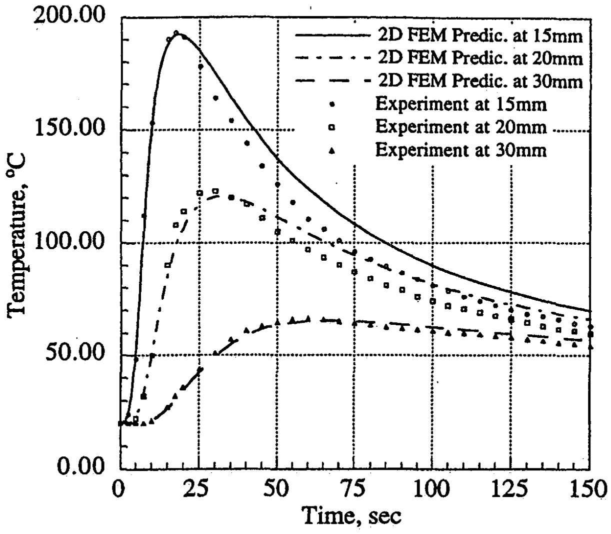


Figure 9 Comparison of predicted transient temperature history vs. experimental results of Specimen 1−1.

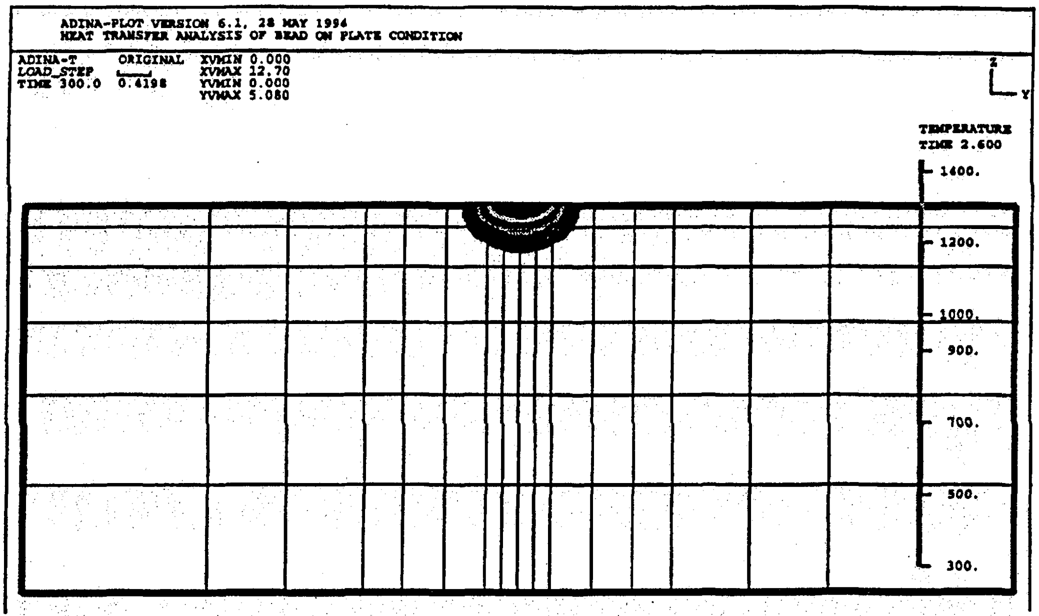


Figure 10 FEM mesh used by Goktug in the analysis of heat flow and transient movement of stainless steel plates heated by a stationary gas tungsten arc.

by a stationary gas tungsten arc⁶⁾. The analytical results agreed well with the experimental results⁴˒⁶⁾.

Figures 6 and 7 show results of 2D FEM predictions for Specimen 1-1 and 1-2, respectively. The analytical results agreed well with the experimental results⁴˒⁶⁾. I must mention, however, that we used a Cray X-MP supercomputer to perform the analysis of transient metal movement of such a simple specimen. An analysis of heat flow and transient metal movement for each case required approximately 2.5 hours of computer time.

However, it was not possible to analytically predict the transient metal movement of Specimen 1-3 especially the metal movement before the weld metal solidified.

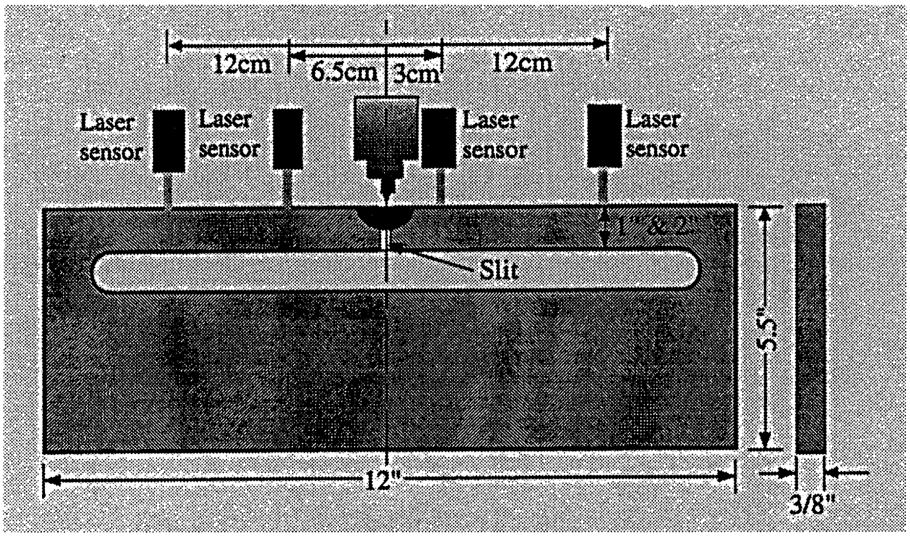


Figure 11 Restrained beam model with bead–on–plate and butt welding at 1" (25mm) and 2" (50mm) deep.

### 3.2 Transient Movement of Restrained Beam Models

Similar experiments were performed on carbon steel plates. **Figure 11** shows the specimen used. The specimens simulate repair welding of railways[4,7)]. Experiments were performed on the following three types of specimens:

Specimen 2-1: Bead-on-plate welding on a continuous beam 1 inch (25 mm) deep

Specimen 2-2: Butt welding of beams 1 inch (25 mm) deep.

Welding was performed by gas tungsten arc process.

Additional experiments were performed on specimens with beams 2 inches (50 mm) deep, but their results are not presented here[7)].

**Figure 12** shows transient displacements of 1 inch deep cantilever beams, Specimen 2-1 without a slit and Specimen 2-2 with a slit. Having a slit makes a fundament difference in transient displacements. The major difference occurred during welding. After welding was completed, the two specimens deformed very similarly. Shown also here are theoretical values using finite element method. In analyzing transient displacements of the specimen with a slit, it was assumed that sections of beams are separated until the weld metal solidified.

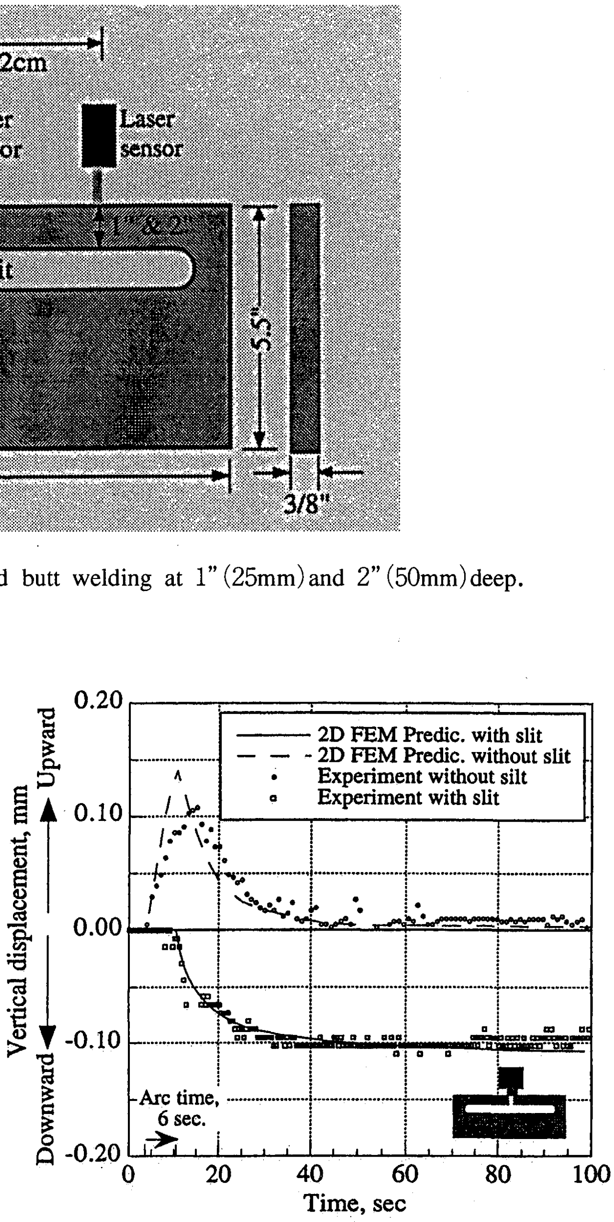


Figure 12 Transsient displacement of 1−inch deep cantilever beam, Specimens 2−1 and 2−2.

Experimental results obtained on specimens using beams 2 inches (50 mm) deep were similar to those obtained on specimens using beams 1 inch, of which results are shown in Figure 12. Therefore, their results are shown here[6)].

### 3.3 H-Shaped Restrained Plate Models

Further experiments were made on out-of-plane distortion produced by welding of H-shaped plate models, as shown in **Figure 13**. Tests were performed on the following two specimens:

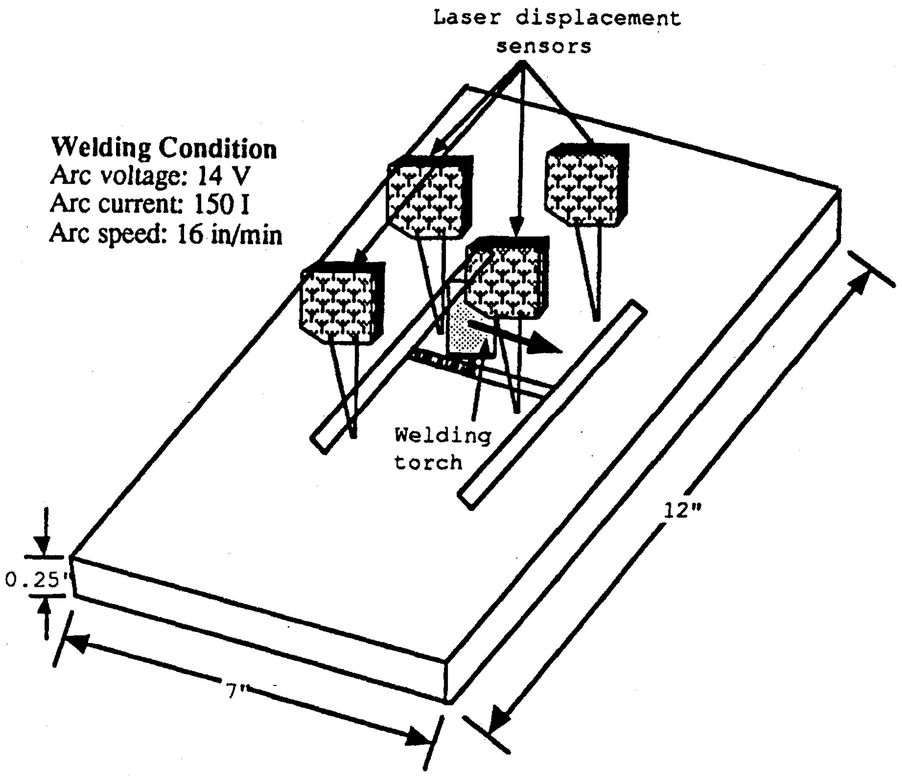


Figure 13 H–shaped restrained plate model with and without a slit.

Specimen 3-1: Bead-on-plate welding along a line

Specimen 3-2: Butt welding along a slit

**Figure 14** shows experimental results on Specimens 3-1 and 3-2. The transient deformations were very different while welding was being performed. With the specimen with no slit (Specimen 3-1). the distortion occurred in one direction during welding and it changed to the other direction after welding was completed just like what is shown in Figure 3. On the specimen with a slit, on the other hand, the plate moved downward as soon as welding started.

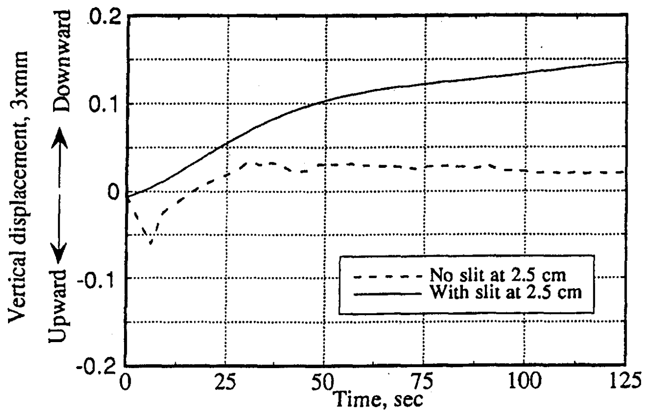


Figure 14 Transient out–of–plane distortion of H–shaped plate specimens.

## 4. Classification of Metal Movements and Distortion Types and Applicability of Current Analytical Techniques

Metal movements that cause weld distortion may be classified into the following three modes[2,4]

Mode 1: Movement of a weldment as a single body due to heating by the welding arc

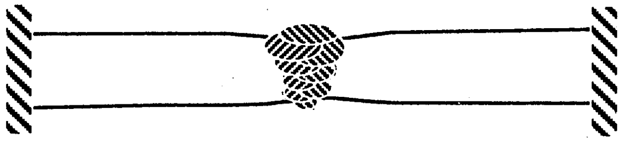
Mode 2: Movements of two separate parts being joined before the weld metal solidifies

Mode 3: Rigid body movements of parts being joined before the weld metal solidifies.

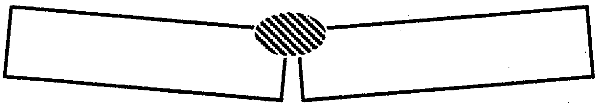
Then, distortions which appear in various types of welded structures may be classified into three types as a combination of the modes listed above as follows:

Type 1: Distortion that involves no

(a) Type 1 distortion that involves only Mode 1 movements caused by plastic deformation produced during welding



(b) Type 2 distortion that involves Mode 1 and Mode 2 movements caused by free surfaces being joined before the solidification of the weld metal



(c) Type 3 distortion caused by Modes 1 and 2 movements and Mode 3 rigid body movements

Figure 15 Three basic types of weld distortion.

topological changes of the piece, as shown in **Figure15** (a). The distortion involves only Mode 1 movement. This type of distortion occurs during: (a) bead-on-plate successive passes in multipass welding of properly restrained parts.

Type 2: Distortion that involves joining of two parts with fixed ends, as distortion involves Modes 1 and 2 movements. Typical cases include(a) the restrained beam specimen with a slit (Specimen 2-1) and (b)the H-shape specimen with a slit (Specimen 3-1). The amount of distortion is medium.

Type 3: Distortion that involves joining of two parts with free ends and no restraining as Specimen 1-3. The distortion involves Modes 1,2, and 3 movements. This type of distortion occurs in welding of free parts. The amount of distortion can be very large.

Regarding analytical capabilities available today, almost all of the efforts performed thus far in the world have been on residual stresses and distortion caused by Mode 1 movements. For example, residual stresses that remain after welding is completed are mainly affected movements. Therefore, many of the analytical studies on residual stresses and distortion in welds performed thus far address residual stresses. It is now possible to analytically determine residual stresses in welds in various geometries including plates, pipes, girders, etc. The same techniques can be used for analyzing distortion caused mainly by Mode 1 movements. For example, it should be possible to analytically determine radial distortion caused by bead-on-plate girth welding of a pipe.

## 5. Comments on the Present State-of-the-Art of Theoretical Prediction of Residual Stresses and Distortion in Welds

I am very pleased to see that it is now possible to calculate using modem computers: heat flow, transient thermal stresses and metal movement, also the residual stresses and distortion that remain after welds have cooled in various simple joints. This is far cry from what was possible until around 1960. Nevertheless, I must say that accomplishment today is limited to cases far simpler than many complex weldments used in many actual structures.

The most orthodox method of theoretically predicting residual stresses and distortion in weldments is to analytically simulate what actually happens during welding$^{2)}$. The analysis usually involves the following steps:

Step 1: Analysis of heat flow
Step 2: Analysis of transient thermal stresses and metal movement during welding
Step 3: Determination of incompatible strains and joint mismatch that remain after welding
Step 4: Determination of residual stresses and distortion caused by incompatible strains and join mismatch that remain after welding.

The great strength of this method is that the analysis follows what actually happens during welding. This method, however, relies on (or assumes) the following:

(a) The analytical methods employed are sufficiently accurate

(b) Computations required can be made at reasonable time and cost.

Unfortunately, we still have many problems.

## 5.1 Insufficient Accuracies of Analyses.

The analyses that have been developed and used do not have the accuracy that users would like to see. Some major problems are as follows:

(1) Complexity of the phenomena involved. Phenomena involved during welding are incredibly complex as follows:

(a) Theoretical simulation of residual stresses and distortion involves analysis of plastic deformation at elevated temperatures. Although many investi-gators have tried, analyses available at the present time are not sufficiently accurate in the authors opinion. The main short fall exists in the analysis of plastic flow at elevated temperatures. When one considers such things as the yielding condition and the modulus of elasticity, we do not really know how to define these properties at temperatures close to the melting temperature. Although many studies have been performed during the last 20 years on analyses of residual stresses and distortion in weldments, most of the studies have developed knowledge by use of advanced computational techniques such as the finite element method. The author believes that very little effort has been made to improve the basic understanding of stresses and strains at elevated temperatures during welding that include melting and solidification.

(b) The unique feature of welding is that two separate parts are joined to become one piece. The final distortion is much affected by the complex transient metal movements during welding as discussed earlier in this paper. However, only address the problem as thermal elastic-plastic problem of a single body. We should pay more attention to transient metal movements during welding of various types of welded joints.

(c) In addition, we cannot always neglect effects of other phenomena such as metallurgical transformation that may occur in the weld metal as well as the heat-affected base metal. In fact, there has been enough evidence that metallurgical transformation has significant influence on residual stresses in weldments in high strength steels[1)].

(2) Lack of important physical data at elevated temperatures

In order to perform analyses of heat flow and thermal stresses and metal movement at elevated temperatures, we need data on various properties including heat conductivity, specific heat, coefficient of linear thermal expansion, modulus of elasticity, etc. There is a serious lack of data on these properties of engineering materials. In order to accomplish orderly development of technologies of theoretical prediction of many subjects related to theoretical prediction on joining and welding, which is the major objective of this international symposium, it is extremely important to organize an international cooperative effort for developing these data.

(3) Error accumulation in a series analysis

The analysis of residual stresses and distortion in a weld involves a series of analyses covering the four steps as described above. The error tends to accumulate at each step. If the analysis involves four steps each having 90% accuracy, for example, the accuracy of the total system is only 66%, since $(0.9)^4=0.656$.

One way, probably the best way, for guaranteeing that the accuracy of analysis being performed is reasonably good is to check analytical results with experimental data. In the studies of transient metal movement during welding of some specimens, results of which are presented in this paper, experimental data were first developed using laser distance sensors. Without these data it would have been impossible to develop analytical results with some confidence. I recognize that the major objective of this symposium is to examine the present state-of-the-art of technologies of theoretical prediction. In my opinion, it is also important to investigate possibilities of generating more experimental data which are critical for evaluating the accuracy of theoretical prediction. Many new measurement techniques have been and are being developed just like the development of analytical techniques. In fact, many newly developed measuring technologies vigorously utilize modern computer technologies.

### 5.2 High Cost of Analysis

Since plastic deformation at elevated temperature is involved, the analyses tend to be very complex and expensive. If one tries to perform a complete analytical simulation, supercomputers are required for analyzing even simple welds. In fact, a supercomputer was used for analyzing heat flow and transient metal movement of Specimen 1-1 which is a very simple weld. One could use a workstation instead of a supercomputer, but the analysis would require many hours of computation. Even using today's most powerful computers, a complete analytical simulation of residual stresses and distortion produced during welding fabrication of complex weldments commonly used for actual, complex structures is impractical, if not impossible.

The high cost of analysis may be justified if it involves very expensive and critical operations such as dynamic movement of an airplane or operation of a huge steel making furnace. The unique nature of welding fabrication is that although the entire cost of welding fabrication may be large, it involves welding of many joints in various types. Therefore, the cost for making each weld is rather small. Consequently, it is impractical to spend a huge amount of funding to perform computations on welds.

## 6. Possible Applications of Theoretical Prediction Capabilities for Solving Various Practical Problems

Although I have made some critical comments on the present state-of-the-art of technologies related to theoretical prediction of residual stresses and distortion in weldments, there are many ways of using these technologies for solving a number of problems related to welding fabrication. Since it is impossible to discuss this subject in any detail in this short paper, I simply mention a few examples performed by our research group at MIT of uses of prediction technologies for solving some practical problems as follows:

(1) Development of technologies for reduction and control of distortion and residual stresses
(2) Research on control of out-of-plane distortion of thin panel structure
(3) Research on metal forming by use of laser line heating.

### 6. 1 Development of Technologies of Reduction and Control of Distortion and Residual Stresses

The ultimate objective of studying residual stresses and distortion in welded structures is to minimize negative consequences of these stresses and distortion. The author believes that the most effective way for reducing distortion is to control the formation of plastic strains produced in regions near the weld. The difficulty is that the necessary control must be made during welding. If the control is correct, the final distortion will be reduced. On the other hand, if the control is incorrect, the final distortion will be increased.

In order to perform correct controls consistently, one must have the following capabilities:

(1) Prediction capability. One must have some idea of what should happen by either analysis, experiments, or experience. Having proper analytical prediction capabilities is extremely useful.

(2) Sensing capability. One must have a proper device or devices for sensing if what should happen is actually happening. For this purpose, our research group at MIT has developed and used several sensing systems including[8]) :

(a) Laser interferometer
(b) Computer-aided dial indicator
(c)Triangulation technique using low-power laser beam
(d) Laser displacement sensor.

Experimental results using laser displacement sensors are presented in this paper.

(3) Control capability. If one finds that what is actually happening is different from what is suppose to happen, it is important that one has the capability of making necessary changes, in real time.

Our group has studied various subjects as follows

(a) Reduction of forces acting on tack

welds during butt welding of steel plates through side heating
(b) Reduction of residual stresses in high-strength steel weldments by side heating
(c) Reduction of radial distortion and residual stresses in circular welded pipes
(d) Reduction of longitudinal bending distortion of built-up beams by differential heating.

Results of these studies have been reported in several publications[1-3,9].

## 6.2 Research on Out-of-Plane Distortion of Thin Panel Structures

Superstructures of naval surface ships including cruisers and destroyers are always built as light structures. Aluminum alloys were widely used before the Falkland Island war in 1982 when aluminum structures of a British cruiser were badly damaged. Recently built ships extensively use very thin steel plates for superstructures. The most common structural unit is a welded panel structure in which transverse and longitudinal stiffeners are fillet welded to a thin plate. Out-of-plane distortion of the plate occurs due to angular changes at fillet welds (see Figure 3 (b)). When the plate is too thin or the spacings of stiffening members are too large beyond certain values, the plate will buckle during welding (see Figure 3 (f)). Therefore, how to control out-of-plane distortions of welded panel structures becomes a very important problem. Facing this problem the US Navy sponsored a large-scale research project on this subject, and our research group at MIT was involved.

An important problem was whether or not the out-of-plane distortion does actually happen during welding fabrication. The MIT team used laser distance sensors (as shown in Figure 4) to monitor transient out-of-plane distortions of during welding fabrication of panels in a laboratory as well as in a shipyard. It was found that buckling does actually happen during welding fabrication. Engineers at the Edison Welding Institute performed FEM study for analyzing mechanisms of buckling distortion produced during welding fabrication of the panel structures. I suppose that results of this investigation will be published soon.

## 6.3 Research on Plate Forming by Laser Line Heating

For many years, oxyacetylene torches have been used for forming and straightening steel plates. Since the 1950's, Japanese shipyards have used line heating with oxyacetylene torches for forming steel plates. A research program on metal forming by laser line heating was performed by our group from 1984 through 1987 for the US Navy through Todd Pacific Shipyards Corporation to determine whether steel plates could be formed by use of line heating with a high-power laser beam[9,10]. Major reasons for performing this investigation were:
(a) Laser forming would be easier to incorporate into an automated fabrication system than the traditional forming technique using oxyacetylene torches.
(b) Material degradation by laser forming would be limited to thin lasers near the surface. Therefore, laser forming may be used for such steels as HY-80 and HY- 130 steels which are sensitive to heating.

Since October 1995, a 30-month long Phase 1 program has been sponsored by the Defense Advanced Research Administration. This program is a part of a large program on Flexible Fabrication. The prime contractor is Rockwell Intemational, and subcontractors include:

MIT
Applied Research Laboratory of Pennsylvania State University
Boeing Co.
Ingalls Shipbuilding Co.
Laurel Sheet Metal Products Co.
Newport News Shipbuilding
Pratt & Whitney

Our group at MIT has been given the task of providing basic information including non-contact real-time measurement of distortion and development of analytical systems. Our work essentially involves the following two types of analyses:
(1) Analytical simulation of transient out-of-plane distortion of plates subjected to laser line heating
(2) Development of an algorithm for determining a proper heating pattem to form a metal plate into a

certain shape.

The objective of the Phase 1 program is to develop necessary information needed to develop automated equipment on laser metal forming to be built if the program is continued to Phase 2. I believe that the results will be published in the near future.

## References

1) K. Masubuchi, Analysis of Welded Structures, Pergamon Press (1980)

2) K. Masubuchi, G. Goktug, and A. Umekuni, Report submitted to Navy Joining Center, Columbus, Ohio from MIT, June 1994

3) K. Masubuchi, Journal of Ship Production, Vol. 9, No. 3 (1993), p. 137

4) G. Goktug, S. Koga, E. Kuswantoro, and K. Masubuchi, presented at the 77th Annual AWS Convention and International Welding & Fabrication Exposition, Chicago, IL, April 1996

5) Laser Displacement Sensors, LB-1000 Series, Instruction Manual Keyence Corporation, Osaka, Japan, 1992

6) G.Goktug, "Real Time Non-Contact Measurement and Analysis for the Control of Distortion During Welding, "Ph. D. Thesis, Department of Ocean Engineering, MIT, June 1994

7) E. Kuswantoro, "Experimental and Analytical Studies of Transient Distortion of Welds," S M Thesis, Department of Ocean Engineering, MIT, June 1995

8) K. Masubuchi, W. H. Luebke, and H. Itoh, Journal of Ship Production, Vol. 4, No. 2 (1988), p. 73

9) K. Masubuchi, The Welding Journal, Vol. 70, No. 12 (1991), p. 41

10) K. Scully, Journal of Ship Production, Vol.3, No. 4 (1987), p. 237

11) K .Masubuchi, Proceedings of an International Conference on Laser Advanced Materials Processing (LAMP'921, June, 1992 , Nagaoka, Japan,Vol. 2, p. 939