THERMOMECHANICAL FORMING OF STEEL PLATES USING LASER LINE HEAT

by

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Archives
Thermomechanical Forming of Steel Plates Using Laser Line Heat

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Abstract

A new method to form steel plates for commercial and naval ship construction is proposed. Laser line heating experiments were conducted at the Naval Research Laboratory, Washington, D.C., using a 15 KW CO₂ laser. These experiments show the feasibility of using laser to form complex shapes, with virtually no material degradation, out of low carbon and high-strength steel plates. A series of complex shapes were produced that could be used in the fabrication of a ship's hull. These shapes include sine curve shape, saddle shape, dish shape, several cone segments, and various screw shapes. Another series of tests where conducted that produced quantitative data on plate deformation for a given line heat pass. These studies showed the correlation between laser power, plate travel speed, and plate thickness. A specific heat input combination produces a maximum bending efficiency. Generally, a higher laser power, and faster plate travel speed produces greater plate deformation. Heat input greater than 65 KJ/in cannot be used, since surface melting and material degradation will result. Studies show that maximum bending efficiency cannot be obtained for plates over 3/4 inch thick.

The bending correlation studies indicate that laser metal forming is a reproducible forming process, that can be precisely controlled. The reproducible nature of the process implies that it can be readily adapted to modern control technologies. An automated laser metal forming system is proposed, that would produce complex shapes with virtually no operator input or control. The complex shapes produced by laser line heating would allow ship designers the flexibility to create intricate hull sections, which might improve current hull construction techniques, or decrease a ship’s hydrodynamic resistance.

Thesis Supervisor: Dr. Koichi Masubuchi
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Chapter 1
Forward

1.1 Tasking Requirement

The work and results of this thesis are part of a larger research effort sponsored by the U.S. Navy and Todd Pacific Shipyards Corporation. This research was initially proposed by Dr. Masubuchi (16) who outlined a three phase, three year, technical proposal of experiments. The research in year one of the proposal was a feasibility study that showed that a laser could successfully form steel plates (even high strength quench and tempered steels) for ship construction. Research in year one was divided into 3 parts or "series" of experiments (Figure 1.1). This thesis details results of the metal forming experiments of Phase 1, Series 2 and 3.

1.2 Purpose

The purpose of the metal forming studies in Series 2 and 3 experiments was twofold:

(1) Complex curvature studies. We wanted to show the unique nature of the laser metal forming process by creating shapes that contained compound curvatures. Specifically, we felt that no other forming process could create the same complex shapes out of steel plate that we formed during Series 2 and 3 experiments. These shapes should be reproducible, be formed from mild or high strength steel, and should be patterned after complex shapes found in a ship's hull such as a bulbous bow.

(2) Bending studies. Presuming that we have a unique and feasible process, the majority of our effort was then concentrated on obtaining quantitative data of the actual bending process. Primary bending effects (laser power, plate travel speed, plate thickness) and secondary bending
effects (forced cooling, beam position, etc.) were investigated. This data gave us explicit knowledge of the bending mechanisms, so complex shapes could be reproduced with maximum efficiency and minimum material degradation.

All of the experiments were conducted at the Naval Research Laboratory in Washington, D.C., using a 15 KW CO₂ laser. Series 2 and 3 experiments were conducted in July and November 1984, respectively.
**LASER METAL FORMING EXPERIMENTS**

**SERIES 1**

1. **SINGLE AND MULTIPLE PASS HEATING**
   1a. Temperature measurements (thermocouples)
   1b. Microstrain measurements (strain gages)

   Materials and thickness
   HY-80: 1/2" thick
   AISI 1018: 1/2" thick

**SERIES 2**

1. **FEASIBILITY STUDY OF FORMING DOUBLE AND COMPLEX CURVATURE SHAPES**
2. **PARAMETRIC STUDY FOR CHARACTERIZING THE OPTIMUM LASER PARAMETERS FOR ANGULAR CHANGE IN VARYING PLATE THICKNESSES**

   Materials and thickness
   A36: 1/4", 1/2" thick

**SERIES 3**

1. **BENDING CORRELATION STUDY**
   1a. Continue parametric studies, series 2,(2) for 3/4" and 1" thick A-36 plates.
   1b. Parametric Study using a 5 kw power input, varying only plate and travel speed
   1c. Bending correlation between position of the heat and plate's edge
   1d. Effect of boundary constraint on bending
   1e. Effect of cooling backside of plate while being line heated

2. **COMPLEX CURVATURE STUDY**
   Produce shapes encountered in marine construction using 18" x 24" A-36 plates

3. **HLA SIMPLEX CURVATURE**
   Produce the same shapes outlined in (2) but using A-710

   Materials and thickness
   AISI A-36: 1/4", 1/2" thick
   A-710: 1/4", 1/2" thick

---

Figure 1-1: Phase 1 Experiments
Chapter 2

Background

2.1 A Description of Current Plate Forming Techniques

In industry, there is a diverse need to bend and form steel into many shapes. The applications are as varied as the shapes themselves, which include tubular structures for offshore oil rigs, automobile bodies, nuclear reactor components, plates for ship hulls, and even everyday eating cutlery. The metal thickness can range from thin sheet metal used in an automobile body to metal plate an inch or more thick, as might be found in a nuclear reactor or submarine hull. There are many manufacturing processes used to form these shapes, but all of the forming processes can be categorized into two primary bending mechanisms: mechanical and thermomechanical forming.

Mechanical forming is a process where steel plate or sheet metal is formed by a press. The force exerted on the metal by the press causes plastic deformation of the workpiece which in turn permanently deforms the metal into the desired shape.

Examples of this forming process are dies which are machines that cut, form, and/or stamp material into a particular shape (such as a component of an automobile body or eating cutlery). A die can make many complex shapes and curvatures. The forming face of the machine is pre-shaped to the desired pattern that will be produced. This forming process is ideally suited for large production runs and rapid forming. In all die forming operations metal thickness is limited. Thicker steel plate would require tremendous force and an impractically large machine. So, to form large or thick steel plate mechanical rollers or breakforming presses are used. Presses and rollers such as these are limited in that only one direction of curvature can be imparted to the steel plate. Double, compound or complex curvatures cannot be made. Moreover, not all of the steel plate can be pressed into curvature, usually the last several inches of the plate cannot be properly
Thermomechanical forming is a process where a heat source (usually a flame) is introduced to the metal surface. As the heat source passes over the surface to be bent, complex temperature changes occur, the yield point of the steel decreases, and transient thermal stresses are developed. Because of these thermal stresses, non-elastic or incompatible strains are produced, which in turn impart permanent plastic deformation to the workpiece after the metal cools.

The most common example of thermomechanical forming is oxyacetylene heating which is used to bend plate in shipyard applications. One use of this thermomechanical process is spot heating, which is used to remove any local distortion that might occur after a metal plate has been welded in place. Welding produces thermally induced strains which distorts an otherwise flat plate. The welded edges of the plate (along with the underlying stiffeners) constrains the plate against motion. A worker must possess a high level of skill to remove these local distortions.

A related application of thermomechanical forming is line heating. Line heating is a process where a plate is heated by one or more parallel passes of an oxyacetylene flame. These straight line passes thermally deform the plate into a simple curvature. Line heating is generally considered a shop practice where plates are formed (or straightened) prior to their placement in a structure.

Forming a curvature by line heating in a shop is not as complex as removing distortion by spot heating in welded plates. However, both processes require a relatively high level of skill. Individuals trained in all aspects of flame forming should possess a solid understanding of the bending process along with a fundamental knowledge of welding metallurgy.

Other thermomechanical forming methods. There are several other more esoteric thermomechanical forming processes that were described in the Ships Structure Committee Report No. 207 (18). These forming methods include plasma arc heating and induction heating. Both heating methods are supposedly more controllable than flame heating, but the high capital expense of the equipment has kept these methods economically unfeasible. Therefore, simple plate bending
by line heating, or local distortion removal by spot heating is best accomplished by an oxyacetylene flame. If design or manufacturing needs warrant the technological advantages of plasma or induction heating, these systems may be developed. However, I hope to show later in this chapter that any improved forming technology will best be served by laser line heat.

Casting and hot forming are ways to form complex shapes and curvatures. This discussion deals only with those methods which form material from flat sheet metal or metal plate. Therefore, casting is not considered since it forms a shape from a molten metal. Hot forming is a mechanical forming process with thermal heating. The thermal heating allows the metal to be more easily shaped and usually reduces the amount of work-hardening and residual stress. However, reduction in metal yield stress has been reported in reference 18. Essentially, this is another mechanical forming process which warrants no further discussion. Additionally, casting and forging are not applicable or economically feasible to the bending of steel plates for shipyard (or similar industrial) applications.

2.2 A Comparison Between Laser Forming and Conventional Forming Methods

The goal of this research is to develop a batch or single-unit manufacturing system that can form steel plates with simple, compound or complex curvature. This technique must be accurate and reproducible, easily automated, and require little skill by the operator or worker. Additionally, material properties must not be significantly degraded. These criteria can be met if laser line heat is used as the energy source to bend steel plate. However, before the development of a laser forming system is justified, it should be determined that current mechanical and thermomechanical processes have inherent limitations that necessitates the development of an improved forming technology.

The following subsections detail the primary limitations of current metal forming methods as applied to a shipyard environment.
2.2.1 Disadvantages of Mechanical Forming

Mechanical forming processes such as dies can form complex shapes, but the metal thickness is limited to sheet metal or very thin steel plate. This process is easily automated and is adapted to high volume continuous production runs. However, a distinct disadvantage of a die press is that thicker steel plate cannot be formed. Also, steel plate is usually processed in small batch manufacturing operations (plate for a ship’s hull for example). So, the high volume continuous production feature that a die press can offer is not needed.

A breakforming press or roller system can be used for thicker steel plate, however, only simple curvature (curvature in one direction) is obtained. Additionally, the cold-work imparted to a workpiece by mechanical forming can lead to a significant rise in the ductile to brittle transition temperature for mild steel (18).

2.2.2 Disadvantages of Thermomechanical Forming

There are several disadvantages with using oxyacetylene flame as a heat source for thermomechanical forming. The oxyacetylene flame is a diffuse heat source that is difficult to control. The controllability and reproducibility of a straightening or bending process is a function of a worker’s ability. Any time human skill is introduced into a manufacturing process, variability of product quality increases and quality control decreases. Depending on the worker’s knowledge of the bending process, the metal may be overheated in one area causing surface melting (and overbending), or underheated in another area causing an insufficient bend.

Oxyacetylene flame heating is generally not approved for bending (or straightening) high strength steels such as A-517 (a quenched and tempered steel whose high strength is attributed to a specific thermal history) (18). If a quenched and tempered steel is heated to a critical temperature, the material properties of the steel will be adversely affected depending on the time spent at that temperature. A rise in the ductile to brittle transition temperature along with a decrease in the
Charpy upper shelf impact energy is usually seen. This is due to several phenomenon including overtempering and possible adverse phase transformations.

To avoid temperatures that can cause excessive material degradation, temperature indicating crayons are used which will melt at a given temperature. Crayons with melting temperatures between 900 degrees F and 1050 degrees F are recommended by the Ship Structural Committee, SSC-207, SSC-235, and SSC-247 (18,19,20) to avoid excessive material degradation of quenched and tempered steels. An additional check on temperature, recommended by the report, is that, "no obvious color should be visible immediately after removing the torch." These are clearly qualitative and gross approximations of the heat input needed to avoid material degradation. If thermomechanical forming is ever to be developed as an approved technique for quenched and tempered steels, then precise control of the heat input (KJ/in) must be known.

2.2.3 Advantages of Laser Metal Forming

Laser metal forming is a thermomechanical process where a defocussed laser beam is directed on a plate surface. Heat input can be precisely controlled by altering the laser power and the speed that the metal plate travels underneath the beam. By irradiating the plate surface with a series of laser line heat passes, in a specific sequence and orientation, many simple and complex curvatures can be formed. This process offers the following advantages:

a. Laser metal forming is reproducible. Each laser line heat pass produces a specific angle distortion depending on the plate geometry, laser power, beam diameter, plate travel speed, and type of steel. The distortion of each line heat pass is additive, so production of a specific curvature can be predicted and easily reproduced.

b. Laser metal forming requires no manual skill. The heat input and sequence of each line heat pass is predetermined. The skill of a shipyard worker (to manually set the heat of an oxy-acetylene flame and determine the torch travel speed) is no longer required with this process.
c. Laser metal forming is easily automated. All primary and secondary equipment related to the forming process (including laser, plate cooling system, etc.) can be controlled and monitored in one area. More importantly, this process is readily adapted to advanced manufacturing technology such as computer control. Since laser metal forming is predictable and reproducible, the forming process could be controlled by an open loop, Computer Numerical Control (CNC) system. In an open loop CNC system the pass sequence, plate speed, and power of each line heat pass can be preprogrammed; the computer merely controls the equipment in a sequence of events without manual input.

If a state-of-the-art automation and monitoring system is desired, a closed loop, Adaptive Control Constrained (ACC) system could be developed. In a closed loop ACC system, a sensing device (such as a laser interferometer and vision system) would be used to monitor the bending process and then provide feedback to the computer. The computer would then vary the input parameters (such as plate travel speed and laser power) until the desired shape or curvature is obtained.

d. Material degradation is negligible. Manual flame heating with an oxy-acetylene torch monitors the plate temperature by temperature-indicating crayons and plate color to prevent material degradation of heat sensitive materials. In contrast, precise line heat control and power input can be achieved with laser. Laser is a superior heat source as compared to an oxy-acetylene flame. The laser beam diameter, power setting and plate travel speed is preset so an exact heat input (KJ/in) is produced. Several studies have been accomplished by Haidemenopoulos (10) and Deacon (5) to determine the heat input parameters required to limit material degradation. Negligible degradation and a shallow heat affected zone is achieved (for selected high strength quenched and tempered steels such as HY-80 and several HSLA's) when heat input is limited to predetermined values. The guesswork of the oxyacetylene line heat process is completely removed by laser line heat.
2.2.4 Additional Arguments for Laser Metal Forming

It can be argued that if the flame heating process could be automated, then the controllability and reproducibility of the process could be greatly improved. For example, if a series of one or more torches could be automatically controlled, this automation would negate the primary disadvantage of flame heating (i.e., manual control). In support of this argument, several flame cutting operations have been automated with computer numerical control in Norway and Germany (2,7,9). If this automated cutting technology could be adapted to flame line heating, then the manual variability of the forming process would be eliminated. However, (1) a literature survey reveals that no such automated forming process exists, and (2) even if such an automated forming process did exist, or if the automated cutting technology could be adapted to forming, I contend that the product quality and reproducibility of the desired curvatures would be limited by the diffuse nature of the oxyacetlyene flame. This point is disputable and should be verified.

The argument to use laser line heat has been limited to forming or straightening plates in a shop environment. Laser line heating does not attempt to replace all uses of conventional mechanical and thermomechanical forming processes. For example, simple curvature is probably best formed by a mechanical press or roller. Secondly, local buckling of a steel plate, already welded in place, is best removed by flame heating. Laser line heating is a technique used to form plates in a shop. The size of the laser equipment, optics and controls makes it impractical to be used for local removal of distorted plates away from the shop. Even if the laser beam could be remotely carried to the ship site (by means of fiberoptics for example), all that would be gained over the use of flame is an improved heat source. This hardly justifies such a remote system since the advantages gained by laser, including precise and reproducible deformation, are not required for spot heat application.

In summary, laser line heat is the best way to form compound or complex curvature from flat plate. This system is easily adapted to the current manufacturing technology and material
degradation is negligible in heat sensitive materials. No automated thermomechanical forming process currently exists and laser line forming offers the greatest technological potential.

Shipbuilding technology has improved little since World War II. A ship's hull is formed by a series of flat and simple curvature plates which are welded together. In certain hull areas where compound curvature is required, such as the sonar dome, bulbous bow, and curvatures in the bow and stern, flat and single curvature plates are welded together. Fabrication and fit-up can be a problem.

If developed, laser line heat can be used as a designer's tool and as an improvement in future shipbuilding technology. Designers and shipbuilders can now design and fabricate compound curvature structures never before considered. Currently, where several plates are needed to form a complex shape, laser line heating could potentially form that same complex shape out of one plate. Not only is the amount of welding reduced, but the material degradation caused by welding would be minimized. Moreover, the hydrodynamic characteristics of flow around these shapes might be significantly improved.

If shipbuilding technology is to advance into the 21st century, then we cannot rely on technology and fabrication practices that are already forty years old. Advancements in manufacturing such as adaptive control and computer automation should be adapted to the shipbuilding industry.
Chapter 3

Physics of Thermomechanical Forming

Thermomechanical forming of a steel plate is a process where the controlled application of thermal expansion is used to impart a movement and plastic deformation of a workpiece. As the heat source passes over the metal surface, the metal undergoes complex temperature changes which cause transient thermal stresses to develop. These stresses then produce non-elastic or plastic strains. In order to obtain these plastic strains (or deformation), the yield strength of the material must be exceeded. The amount of thermal expansion resulting from heating steels to a given temperature can be considered constant since the coefficient of thermal expansion varies little among many structural steels. The amount of plastic strain available for use in deforming a plate is therefore that portion of the thermal strain which exceeds the yield strain at the yield strength of the material. Thus, the amount of deformation that can be achieved from thermomechanical forming is a function of the yield strength of the material (12,13). If two steels used in ship construction, A-36 (\(\sigma_y=36\)KSI) and A-517 (\(\sigma_y=80\)KSI), were given the same heat input, the A-517 would deform less. Alternatively stated, the effectiveness of laser line heating decreases as the yield point \(\sigma_y\) of the material increases. This fact is graphically shown in Figures 3.1 and 3.2 (12).

The temperature rise to initiate plastic flow is the intersection of the total thermal expansion and elastic strain curves. The plastic flow curve is the elastic strain subtracted from the total thermal expansion. This plastic strain is the maximum change of shape that can be imposed without any outside force (12).

Thermomechanical forming is based on a fundamental principle that plastic flow of a material can only take place if there is some restraint against which the plastic flow can act. An example is offered for clarification. If a completely unrestrained plate is heated uniformly to slightly below its
Figure 3-1: Thermal Strain Behavior of A-36 Steel Confined Perfectly in One Axis

austenitizing temperature ($A_1$) and then allowed to uniformly cool, no deformation will take place. The temperature reached is clearly beyond that which would initiate plastic flow in a restrained plate, but because there is no restraint the plate will merely expand by $\alpha \delta T$ (where $\alpha$ is the coefficient of thermal expansion (in/in degree F) and $\delta T$ is the temperature rise in degrees F) and then contract by the same amount. This reasoning explains the condition stated in Figures 3.1 and 3.2 that the material is confined perfectly in one axis. If this restraint was not imposed the material could not flow plastically.

In laser line heating, the heat source travels on a straight-line path along one axis of the plate. The restraint against which the plastic flow acts is the surrounding plate material which was not or is not directly irradiated by the laser beam. The plate material directly underneath the laser beam is significantly hotter than the surrounding plate material. The restraint of the heated zone is furnished by the "cold" metal on the sides, in front of, and underneath the line to be tracked.
Figure 3-2: Thermal Strain Behavior of A517 Steel Confined Perfectly in One Axis

Thus, the bending mechanism can be summarized as follows: If a plate is heated along a line past the temperature where plastic flow will initiate (a function of $\gamma$), the metal will expand and be placed in a state of compression due to the restraint of the surrounding "cold" metal. The irradiated surface of the plate is hotter than the bottom surface of the plate and the plate will deform negatively (concave down). As the plate cools, the plastically deformed heated metal contracts and goes into a state of tension. The plate will then rotate and deform positively (concave up) as it seeks an equilibrium position due to this residual tensile stress. As a side note, since residual stresses exist without external forces, the resultant force and the resultant moment produced by the residual stresses must vanish (15).

This leads to the conclusion that any residual tensile stress caused by the line heat will be balanced by a compressive residual stress in that same plane section. If successive line heat passes are used to form a complex shape in a plate, and since the stress produced by each pass is additive,
then it is possible that the overall residual stress produced by line heating is relatively low (as compared to mechanical bending). Additionally, Holt (12) states that properly placed heat patterns produce a residual stress pattern that is lower in magnitude and more uniform than as-rolled material. However, for a given bend, the residual stress induced by line heat should be compared to the residual stress induced by mechanical bending.

3.1 Primary and Secondary Factors Which Affect Deformation

There are several observations that can be deduced from the discussion so far. There are certain factors that significantly contribute to the bending process; these will be called primary factors:

1. *Yield Strength*. The amount of plastic flow (and deformation) depends on the yield strength of the material. Therefore, it can be expected that high strength steel such as HY-80 and A-710 will deform less than A-36 for a given heat input.

2. *Laser Power and Plate Travel Speed*. Deformation depends on the maximum temperature obtained during the line heat pass. This temperature in turn depends on the combination of the laser power and how quickly the plate passes under the laser beam. (This is the heat input expressed in KJoules/inch). More heat input (implying a higher temperature) is not always beneficial. If the laser power is too high or the plate travel speed is too low, too much heating will occur and the plate will not achieve maximum bend. This is because too much of the surrounding material was heated which results in insufficient restraint against plastic flow. The bending mechanism depends on the through thickness temperature differential. Too much heat input results in a higher temperature on the opposite side of the plate to the side being heated which, in turn, decreases the ΔT across the plate thickness. Conversely, if the laser power is too low or the plate travel speed is too high, insufficient heat input will result. Insufficient heat input does not raise the plate temperature under the heat source sufficiently to achieve efficient plastic flow (or
bending) of the plate.

3. *Plate Thickness.* Heat input and the resulting bend are closely related to the plate thickness as was described in the previous paragraph; there is a heat input that yields an optimum bend for a given plate thickness. However, if the plate becomes thicker and thicker, heat input would correspondingly get higher and higher. Two practical limits would ultimately be reached: (1) the temperature corresponding to a given heat input would become so high that surface melting would occur and (2) the plate would become so thick that the volume of material would restrain the plate against motion, no matter how much heat input was delivered.

There are several other factors that affect the bending process. These factors do not have as pronounced affect as the three primary factors just described, but their effect is significant; these will be called secondary factors:

1. *Edge Restraint.* The plastic flow of a heated material depends on the surrounding restraint of cooler material. If one edge of a plate is clamped (imposed additional restraint), it can be deduced that the closer the line heat is applied to this restraint, more bend should be produced. A boundary constraint will virtually increase the plate's dimensions and offer additional resistance to the plastic flow of the material.

2. *Heating Location.* Related to the argument in the above paragraph, as the line heat is applied closer to a free edge of a plate, less bend should be seen. This effect is caused by two factors: First, there is less material to act as a heat sink close to the plate's edge. This results in greater heating of the through thickness of the plate and subsequent decrease in $\Delta T$. Less temperature differential across the thickness means less material restraint against plastic flow. Second, and similarly, as the line heat pass approaches the plate's edge, there is less material to act as a heat sink in the plane dimension of the line heat pass. The material between the line heat pass and the edge of the plate will approach a critical dimension where it becomes too narrow; its temperature will rise to the point where it offers insufficient restraint against plastic flow.
3. **Applied Cooling.** Additional cooling supplied to the side of the plate opposite the heat input (backside of the plate) should increase the temperature differential and subsequently improve the bending efficiency. It follows that different media which either conduct or convect the heat from the back side of the plate would offer different bending efficiencies.

4. **Geometric Constraint.** As a first order approximation (excluding edge effects), a given line heat pass and heat input will yield a unit rotation or bend of the plate. The effect of each line heat pass is additive. However, a point is reached where if enough passes are made upon one another (or orthogonal to one another) the geometry of the produced shape will offer geometric constraint against further bending. Therefore, our unit bend per pass will approach a limit where additional passes offer negligible bend. This implies that the plastic flow of the material is limited by the associated residual stress of previous passes. This phenomenon is discussed further in the next paragraph and experimental results are shown in Chapter 5.

5. **Prestrain of the Plate.** Any strain due to residual stress or mechanically imposed stresses prior to heating will alter the behavior shown in Figures 3.1 and 3.2. If compression is present, the elastic strain curve will be shifted down, and the temperature rise required to initiate plastic flow will be decreased. Conversely, if tension is present, the elastic strain curve will be shifted up and the temperature rise required to initiate plastic flow will be increased. Therefore, if we assume that a series of passes on a plate surface puts that plate surface in tension, additional passes (using the same heat input) would produce less bend. Additional discussion is found in references 12 and 20. With respect to mechanical strain, prior cold work (as found in rolled steels) would alter the amount of heat required to initiate plastic flow, as compared to steel plate that has not been rolled. Moreover, less plastic flow would be seen in the recrystallization range (12).

6. **Laser Spot Size.** Masubuchi, in association with the Japanese Welding Engineering Society (11), conducted preliminary studies on the effect of beam spot size on angular distortion. The results are graphically depicted in Figure 3.3. At a heat input of 24 KJ/in, spot diameters of less than 27mm produced surface melting and less than one degree of bend per pass. A spot diameter
of 66mm (2.6 inches) did not melt the surface and produced over one degree of bend per pass. There are no data points between 27 and 66mm. This effect should be further investigated by subsequent researchers.

7. Coupling Between the Heat Source and the Plate. Laser line heat has an advantage over conventional oxyacetylene flame heat in that the power input to the plate can be precisely controlled. However, what is not known is the amount of the beam that is actually absorbed by the plate. The laser beam is either absorbed or reflected off the plate surface. The absorption is a direct function of the coating (paint, oxide layer, etc.) on the plate surface. For example, a shiny metallic plate surface would only absorb a fraction of the beam power, as compared with a plate surface that is covered with a beam absorbing coating (such as black paint).

3.2 Mechanics of Bending - Empirical Results vs. Numerical Prediction

Several theoretical and numerical models have been established to predict the strains (and ultimate deformations) of plates subjected to transient thermal loads. Advances in theoretical stress analysis, due to the widespread availability of computers, have brought about the capabilities necessary to represent the behavior that occurs during high temperature heating (13). A combined program of experimental results and mathematical stress analysis represents a powerful tool for predicting deformation due to transient thermal heating.

Mathematical prediction of stress and strain distribution in a line heated or welded plate is a complex analysis. First, one must accurately simulate on a computer, or find a closed form analytical solution, to a three-dimensional heat flow problem. This phenomenon is not only transient, but it involves nonlinear convection and radiation boundary conditions. Secondly, there is no accurate thermo-elastic-plastic model that accurately couples simultaneous thermal and mechanical effects. Therefore, an analysis of the thermal history (usually obtained by experimental results) is used as an input for subsequent stress and strain analysis. The stress and strain analysis
Figure 3-3: Effect of beam spot size on angular distortion produced by laser line heating
of a thermally loaded material must then account for temperature dependent properties such as thermal conductivity, specific heat, density and yield stress. Several investigators (1,13) have developed computer models that can account for such complex thermal and stress analysis.

A computer model that could predict thermally induced stress and strains would be beneficial to the analysis of the laser line heat process. In fact, Johnson (14) in Phase I of this project has taken real-time temperature and strain data for future use in a predictive computer model. However, even though a computer model would be beneficial for deformation analysis, it is not necessary to fulfill the final objective of this research. The goal of this project is to develop a reproducible, controllable and automated system to form metal plates. To this end, a significant amount of empirical research has been accomplished on the primary and secondary factors which affect plate deformation by laser line heat. This data shows that laser line heating is a predictable and reproducible process. The predictability allows the experimental results to be used in a simplified computer model which does not need thermal-stress-strain relations to predict the final shape. Therefore, an adequate, empirically based design tool can be created without the use of complex stress-strain analysis (see Chapter 7).

Most importantly, the final goal of this research is to develop an automated system. This automated system would incorporate a closed-loop, adaptive control monitoring system which would enable the system to sense and regulate plate distortion. Real-time regulation and control allows the system to sense transient and final distortion. A computer stress-strain analysis or an empirically based model is a strong predictive tool, however, real-time analysis does not need predictive capabilities when in-process parameters are being monitored.
Chapter 4
Experimental Procedure

4.1 Experimental Set-Up

All experiments were conducted at the Naval Research Laboratory, Washington, D.C. using their 15 KW CO$_2$ laser manufactured by United Technologies. The laser had a continuous beam output with a wavelength of 10.6$\mu$m (infrared region). A defocused beam was used that had a diameter of about 1.5 inches (specifically, 1.5 inches (38.1mm) diameter was used during Series 2 experiments and 1.63 inches (43.1mm) was used during Series 3 experiments. The selection of a 1.5 inch beam diameter was somewhat arbitrary (the only previous study done on beam diameter versus resultant degree bend was a study done by Masubuchi (11) which showed the effects of a beam 27mm and 60mm in diameter). The beam produced a "top hat" pattern which is shown in Figure 4.1.

In all line heat passes, the laser beam was fixed and the plate travelled underneath the beam on a milling machine table. The optics of the laser dictated the set-up of this arrangement. If the beam moved over the workpiece, uniform beam diameter and intensity would be difficult to guarantee. Positive and negative "X" direction plate motion was driven by the motor on the table. Direction and motor speed were remotely controlled. Positive and negative "Y" direction motion were manually positioned by a hand-crank on the table prior to each pass. The general arrangement of the system was identical to the one used by Johnson (14) during Series 1 experiments (Figure 4.2).

The beam wavelength was in the infrared region. This wavelength gives the beam excellent heating characteristics, but it is invisible to the human eye. Therefore, no one was allowed in the workspace when the actual bending was taking place. The laser and the milling machine table
were remotely controlled at a control station in an adjacent room.

Figure 4.3 depicts the reflective properties of a series of wavelengths from 0.1 to 10.6 µm (8). At 10.6µm, the reflectance is nearly 100% for all metals. This would imply that for a CO₂ laser there would be almost zero energy transfer to a metallic surface, if the power density is below that which would cause melting, Figure 4.4 (6). Therefore, all plate surfaces were coated with a standard flat black spray paint to improve the coupling of the beam to the plate surface by reducing reflectivity. We are not certain how much coupling was affected by the spray paint, but the energy transfer was sufficient for adequate bending.

Depending on the experiment, the plates either rested on the motor driven table surface or they were clamped in a specially designed clamping fixture (Figure 4.5). The clamping fixture provided edge restraint and allowed for quick removal and insertion of test plates. Also, clamping one edge provided a means to measure plate displacement immediately after a pass of line heat.
Figure 4-2: Sketch of the Laser Facility at NRL
Figure 4-3: Reflectance versus Wavelength

By taking a dial gage reading on the edge opposite the clamped edge before and after the line heat pass, vertical distortion could be measured. Knowing vertical distortion and the distance from the plate's edge to the beam path center, total distortion $\Theta_f$ was directly measured by the relation:

$$\Theta_f = \arctan(X/\Delta Y)$$  \hspace{1cm} (4.1)

$\Theta_f =$ total plate rotation  
$X =$ distance from the plate's edge  
$\Delta Y =$ relative vertical displacement

After a line pass, the plate would rotate slowly as it would cool deform into it's final permanent shape. To decrease the cooling time, forced air convection was directed between the work table and the plate.

The energy input by each line heat pass was determined by the Joules of energy per inch of travel over the plate surface. We had control over the laser power output and the plate travel speed so we could precisely set the energy delivered to the plate surface. The heat input, expressed
in KJ/inch, was determined by the following simple expression:

\[ \text{Heat Input} = (P/V) \times 60 \]  

(4.2)

\[ P = \text{laser power (KW)} \]
\[ V = \text{plate travel speed (inches per minute)} \]

Normally there was a 10% loss of power between the laser and the plate due to optic losses. All power and energy input values in this thesis account for this 10% loss; all values describe the energy or power at the plate surface.

4.2 Measuring Techniques - Laser Interferometer

Measurements of plate distortion were obtained during the experiments at the Naval Research Laboratory by the use of a dial gage. A dial gage provided a quick means to spot-check plate deflection, but there were several limitations inherent to this instrument as used in the set-up.
Figure 4-5: Clamping Device Used in Series 2 and 3 Experiments
shown in Figure 4.5.

1. **Boundary constraint** - The boundary constraint (one edge of the plate clamped) was needed to provide a reference plane from which distortion was measured. But, as described in Secion 3.1, a boundary constraint provides resistance against plastic flow and will increase apparent distortion. Therefore, if distortion measurements were taken on line heat passes between the plate centerline and the clamped edge, boundary constraint effects would be present and anomalously high distortion would be seen. However, if distortion measurements were taken on line heat passes between the plate centerline and the far edge (the edge opposite the clamped edge), no boundary constraint effects were seen. Therefore, this measuring set-up was limited, in that line heat passes on only one-half of the plate could be measured accurately.

2. **Mechanical contact** - A dial gage rests on the surface of the plate and is therefore subject to surface irregularities (high and low spots). We tried to ensure the gage measured plate distortion from the same location before and after the line heat pass, but this could not be guaranteed.

3. **Cooling time** - After a line heat pass, the plate would rapidly rotate into its deformed position. Within 3-5 minutes after heating the plate would assume at least 95% of its deformed shape. However, cooling times of 15-30 minutes were needed for 100% distortion after a line heat pass. This complete cooling time made measuring 100% distortion prohibitively long, so the measurements that were taken are subject to (roughly) 5% error.

It should be emphasized that dial gage measurements were only used as spot-checks of on-site distortion. This information proved valuable for trend analysis and was an aid in helping us understand the bending mechanisms of laser line heating. Accuracy of this technique was within .1 degree.

However, several of the bending studies performed could not have a boundary constraint, and the dial indicator (which required a clamped edge) could not be used. These plates were not measured at the Naval Research Laboratory, but were shipped back to M.I.T. where they were measured by a laser interferometer. Also, plates that were measured by a dial indicator were measured by the laser interferometer for an accuracy and comparison check.

### 4.2.1 Laser Interferometer

A laser interferometer is a non-contacting, optical measuring device that uses an expanded, split laser beam (usually from a low power helium neon laser source) to measure out-of-plane
distortion of a surface. The laser interferometer used for these measurements at M.I.T., Figure 4.6, was developed by Cook (17) as a special project for Prof. Masubuchi. The following system description and figures are taken from reference 17.

The laser interferometer uses a 5 milliwatt helium neon laser as monochromatic light source which has a wavelength of 6328 angstroms. The laser beam is expanded, columnated, and split into two phase-locked overlapping beams by two concave mirrors, as shown in Figure 4.7.

![Diagram of Laser Interferometer](image)

**Figure 4-6: Laser Interferometer Developed at M.I.T.**

The two overlapping beams cause a series of parallel interference fringes composed of alternating dark and bright vertical lines which will appear on a surface placed anywhere in the overlap zone. Each bright fringe is produced when the optical path length difference between the
point source and the position on the specimen corresponds to an integral multiple of wavelengths so that constructive interference occurs. Each dark fringe is produced when this path length difference corresponds to an odd multiple of half wavelengths so that destructive interference occurs. Within the beam overlap zone, the loci of constructive and destructive interference points map as alternating planes that run parallel to the beam axis and normal to the paper as shown in Figure 4.7. This system was developed to measure distortion in plates that were fillet welded. However, it can be used to measure any out-of-plane plate distortion in specimen sizes up to 18 inches long.

Figure 4-7: Laser Interferometer Optics

The beam overlap zone is directed outside the optics enclosure and is directed specimen as shown in the lower left corner of Figure 4.6. In this case, the specimen is mounted in a vertical
plane where it can be rotated to any specimen mounting angle, $\omega$. Also by rotating the split mirror and the two flat beam folding mirrors by 90 degrees, the interference fringe planes can be rotated 90 degrees which permits distortion measurement in horizontal plane. This is what was done to measure the distortion of the laser line heated plates.

The plate was painted with a light coating of red primer spray paint to enhance the light and dark fringes. The plate was mounted horizontally to the incident planes of horizontal light and dark fringes. The horizontal angle of incidence (or mounting angle $\omega$) was kept between 80 and 90 degrees so the specimen surface fringe spacings, $s$, were equal to the zone fringe plane spacing, d. These are related by the following equation:

$$s = d / \cos \omega$$  \hspace{1cm} (4.3)

The longitudinal bend caused by the line heat pass would produce a fringe pattern similar to that shown in Figure 4.8.

The spacing between two adjacent fringes is measured for each of the two points, $P_1$ and $P_2$, on the specimen, between which the angle is to be measured. For each fringe spacing, the effective specimen mounting angle is then computed. The total bend, $B$, is simply the difference of the mounting angles:

$$B = \omega_1 - \omega_2 = \cos^{-1}(h/s_1) - \cos^{-1}(h/s_2)$$ \hspace{1cm} (4.4)

$B =$ total bend angle  
$\omega_{1,2} =$ mounting angle at $P_1$ and $P_2$  
h = contour change  
$s_{1,2} =$ fringe spacing at $P_1$ and $P_2$

The fringe spacing, which is measured manually, is on the order of 2-3 mm, and it is often difficult to get an accurate measurement. Measurement accuracy is limited to 0.1 degree. Also, because of the beam overlap zone width, the maximum plate deflection that can be measured is about 1 inch. One inch is adequate for plates with one line heat pass, however, plates with many passes and much distortion could not be measured with this instrument.
Figure 4-8: Fringe Pattern on a Plate with One Line Heat Pass
Chapter 5
Experimental Results

5.1 Bending Correlation Studies

Laser metal forming had several advantages over conventional thermomechanical forming processes. These advantages include reproducibility and adaptability to automation. This implies that there are quantitative and reproducible correlations between the laser, plate travel speed, plate type, plate thickness, etc., which would eliminate the need for human skill and judgment. Our goal then, was to establish these quantitative correlations as a series of bending parameters which we categorized into primary and secondary bending factors. As described in Chapter 3, primary effects are those parameters which have a significant impact on the bending process (such as power, plate travel speed, plate type, and plate thickness). Secondary factors affect the bending process to a lesser extent; they either (1) optimize primary bending factors such as use of applied cooling, or surface coatings or (2) are bending phenomenon such as plate restraint, edge effects and geometric constraints.

With this data, a quantitative base is established so that a proposed series of line heat passes will mathematically predetermine a final distortion prior to the formation of the actual shape. Complex shapes could then be precisely formed and reproduced without a worker’s input as to metallurgical and mechanical bending considerations.

5.1.1 Primary Bending Factors

Primary bending factors are material yield strength (function of material type), laser power and plate travel speed, and plate thickness. A series of studies were done on ASTM A-36, mild steel that related all three parameters (laser power, plate travel speed and plate thickness). These
studies were called parametric studies since they involved the three primary parameters which affect bending.

5.1.1.1 Parametric Studies

Depending on the plate thickness, a certain combination of laser power and plate travel speed will yield an optimum bend. As discussed in Chapter 3, if the heat input is too great, the plate will overheat, there will be a decrease of resistance against plastic flow, and inefficient bending will result. If the heat input is too little, insufficient plastic flow will result, and again, there will be an inefficient bend. These effects are graphically shown when the parameter \( P/\sqrt{V} \) is plotted against \( \theta_f \).

Data for 1/4, 1/2, 3/4, 1 inch A-36 mild steel plate is listed in Table 5.1 under "original parametric study", which gives all plate sizes and input parameters. Figures 5.1 through 5.3 plots the same data in Table 5.1 in the following 3 ways to illustrate specific conclusions about the bending process.

1. Figure 5.1: Plots the parameter \( P/\sqrt{V} \) vs. \( \theta_f \)
2. Figure 5.2: Plots heat input vs. \( \theta_f \)
3. Figure 5.3: Plots the parameter \( P/t\sqrt{V} \) vs. \( \theta_f \)

Figure 5.1 shows that an optimum combination of laser power and plate travel speed is reached for plates that are 1/4 inch and 1/2 inch thick. This optimum value corresponds to the maximum degree bend versus parameter \( P/vv \). Past this point, the plates become overheated and the temperature differential is not great enough in the through thickness and plane dimensions to cause efficient bending. The curves for 3/4 inch and 1 inch A-36 mild steel never reach a maximum or optimum bend vs. parameter \( P/\sqrt{V} \). This is primarily due to the fact that a practical upper bound is reached; at this upper bound, the combination of laser power and plate travel speed produces a heat input that exceeds 65 KJ/in. Heat inputs in excess of 65 KJ/in result in surface melting and excessive material degradation. This is clearly unacceptable since our goal is to
develop a metal forming system that does not degrade the base metal or reduce the mechanical performance of the material. Therefore, laser metal forming can form thick plates \( t > 3/4 \) inch, but the process is relatively inefficient. Also, deformation up to .75 degree/pass can be produced, but only at heat inputs exceeding 55-60 KJ/in. High heat inputs such as this will probably not affect mild steel, but Haidemenopoulos (10) has shown that fracture toughness is degraded in both HY-80 and K-TEN80CF steel when single pass heating of 54 KJ/in was used.

Figure 5.2 plots heat input (KJ/in) vs. \( \Theta_f \). Bending data was plotted against energy to show the relative efficiency and the energy required to achieve a particular bend for various plate thicknesses. Two obvious conclusions are drawn from Figure 5.2: (1) for a given value of heat input, the amount of angular distortion increases as plate thickness decreases, and (2) for a given plate thickness, the amount of angular distortion increases as the heat input increases until a maximum efficiency is reached. Results for the 1/4 inch plate show that this maximum is reached at 19.0 KJ/in. However, at 19.4 KJ/in a rapid decrease in bending efficiency is seen as the plate becomes overheated. A sharp drop such as this requires further experimentation and testing to confirm the phenomenon.

It should be noted that the data for the 1/2 inch plate was plotted using the data found in Table 1 under "additional parametric study." This was done because there was an anomalous correlation in the 1/2 inch original parametric study; 31.5 KJ/in produced more bend than 33.5 KJ/in. This data was skewed because the bend is also a function of the plate travel speed. Therefore, the data for the 1/2 inch "original parametric study" should be taken again, making sure that heat input is constantly decreasing. As a final point, since there is a wide gap in bending efficiency between 1/4 inch and 1/2 inch, a parametric study should be done for 3/8 inch plate.

Figure 5.3 plots the data in Table 5.11, but it normalizes each point by dividing the parameter \( P/\sqrt{v} \) by the plate thickness, \( t \). All normalized data points plot along a fairly narrow range of values. This narrow range implies that the bending mechanism is, on a first order approximation, the same for all plates. Therefore, the bend for any plate thickness between 1/4 - 1
inch can be estimated. For example, the power and plate speed requirements, $P/\sqrt{v}$, for a given angular distortion could be estimated for a 3/8 or 5/8 inch thick plate from Figure 5.3. The range of data is too wide for an exact approximation, but a reasonable first order approximation is valid.

Also, this data shows that the degree of angular distortion varies linearly with plate thickness. We speculated that as the plate became thicker, the degree of bend (normalized for thickness) would decrease geometrically or exponentially due to the restraint of the surrounding material. Figure 5.3 shows that this hypothesis is not necessarily valid for plates less than or equal to 1 inch thick. This implies that thicker plates bend less than thin plates, but the bending mechanism remains constant.

5.1.1.2 Parametric Study - Constant Power Input

A parametric study will yield the optimum angle deflection for a given plate thickness and power input, divided by the square root of plate travel speed. The two variables that can be arbitrarily chosen to yield a given deflection are therefore laser power, $P$, and plate travel speed, $v$. A constant parameter $P/\sqrt{v}$ does not necessarily mean a constant deflection if power and plate travel speed are not equal. For example, if $P/\sqrt{v}$ is chosen to be 2.0 then two different arbitrary values of power and velocity will both yield $P/\sqrt{v} = 2.0$, but the degree of deflection is vastly different. The following data is offered for clarification:

<table>
<thead>
<tr>
<th>Power</th>
<th>Velocity</th>
<th>$P/\sqrt{v}$</th>
<th>KJ/in</th>
<th>$\Theta_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>12</td>
<td>2.0</td>
<td>31.5</td>
<td>0.90</td>
</tr>
<tr>
<td>5.0</td>
<td>6</td>
<td>2.0</td>
<td>50</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The parameter, $P/\sqrt{V}$, yields 31.5 KJ/in and 0.90 degree deflection while it can also yield 50 KJ/in and 1.23 degree deflection. We speculated that a 5.0 KW laser would have a significantly lower initial capital outlay than a 15 KW laser. Therefore, an additional parametric study was run to compare the angle deflection variation between a constant 5 KW source (with variable plate travel speed) versus a variable power source (with variable plate travel speed). This data would provide an optimum bending correlation in the event that a 5 KW laser was chosen as the power.
Table 5-1: Process parameters and test results obtained in parametric studies

<table>
<thead>
<tr>
<th>THICKNESS (in)</th>
<th>SIZE (in)</th>
<th>POWER (kw)</th>
<th>SPEED (ipm)</th>
<th>HEAT INPUT (kJ/in)</th>
<th>$\frac{P}{\sqrt{v}}$</th>
<th>$\frac{P}{\tau \sqrt{v}}$</th>
<th>$\theta_f$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>5 x 10</td>
<td>8.1</td>
<td>25</td>
<td>19.4</td>
<td>1.80</td>
<td>7.2</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.3</td>
<td>20</td>
<td>18.9</td>
<td>1.56</td>
<td>6.24</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>16</td>
<td>16.9</td>
<td>1.25</td>
<td>5.0</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7</td>
<td>12</td>
<td>13.5</td>
<td>0.86</td>
<td>3.44</td>
<td>0.48</td>
</tr>
<tr>
<td>1/2</td>
<td>12 x 12</td>
<td>11.4</td>
<td>16</td>
<td>42.8</td>
<td>3.17</td>
<td>6.34</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.3</td>
<td>12</td>
<td>31.5</td>
<td>2.02</td>
<td>4.04</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>8</td>
<td>33.8</td>
<td>1.76</td>
<td>3.52</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7</td>
<td>6</td>
<td>27.0</td>
<td>1.22</td>
<td>2.44</td>
<td>0.20</td>
</tr>
<tr>
<td>3/4</td>
<td>12 x 12</td>
<td>10.5</td>
<td>10</td>
<td>63</td>
<td>3.32</td>
<td>4.43</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.0</td>
<td>12</td>
<td>55</td>
<td>3.17</td>
<td>4.23</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>12</td>
<td>45</td>
<td>2.6</td>
<td>3.47</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>8</td>
<td>37.5</td>
<td>1.76</td>
<td>2.35</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td>12 x 12</td>
<td>10</td>
<td>9</td>
<td>66</td>
<td>3.33</td>
<td>3.33</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>9</td>
<td>60</td>
<td>3.00</td>
<td>3.50</td>
<td>0.64</td>
</tr>
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<td></td>
<td></td>
<td>7</td>
<td>8</td>
<td>52.5</td>
<td>2.47</td>
<td>2.47</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8</td>
<td>37.5</td>
<td>1.76</td>
<td>1.76</td>
<td>0.12</td>
</tr>
<tr>
<td>Additional Parametric Study</td>
<td>12 x 12</td>
<td>5</td>
<td>12</td>
<td>25</td>
<td>1.44</td>
<td>2.88</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>1.58</td>
<td>3.16</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8</td>
<td>37.5</td>
<td>1.76</td>
<td>3.52</td>
<td>0.92</td>
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<td></td>
<td></td>
<td>5</td>
<td>6</td>
<td>50</td>
<td>2.04</td>
<td>4.08</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>5</td>
<td>60</td>
<td>2.24</td>
<td>4.48</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Note: ① Laser power reflects kw input at the plate surface (after the 10% optical loss)

② The amount of final angular distortion after the plate cooled to room temperature

Table 5-1: Parametric Studies - Process Parameters and Test Results
Figure 5-1: Parametric Study - $P/\sqrt{V}$ vs. Angular Distortion
Figure 5-3: Parametric Study - $P/t\sqrt{v}$ vs. Angular Distortion
source for a prototype system. The results are shown in Table 5.1 under "original parametric study", 1/2 inch plate and "additional parametric study", 1/2 inch plate. This data is plotted in Figure 5.4. The graph shows that the same maximum bend (1.4 degrees) can be achieved with a 5 KW power level at 5 inches per minute as with an 11.4 KW power level at 16 inches per minute. However, two points must be noted:

1. The heat input is 60 KJ/in and 42.8 KJ/in respectively. Therefore, if a 5 KW source was used to achieve 1.4 degrees of bend, the heat input would cause a reduction in fracture toughness in high strength quench and tempered steels.

2. The production time would increase by a factor of 3 if a 5 KW heat input is used. This would be a significant factor if this process was adapted to bend large steel plates. For example, if a 10 foot plate was distorted 1.4 degrees with one pass, the constant 5 KW laser power at 5 ipm would take 24 minutes while, 11.4 KW laser power at 16 ipm would take 7.5 minutes.

Clearly, if higher laser power and faster plate travel speed is used, less energy is required, faster production time is realized, and material degradation is less. Simply stated, high power and fast plate travel speed are an efficient bending combination. A 12-15 KW laser will have a higher initial capital cost than a 5 KW laser, but the savings in production time might justify the expenditure. An economic analysis between these tradeoffs should be done before a prototype system is developed.

5.1.2 Secondary Bending Factors

Secondary bending factors are those variables which effect the bending process but have a minor affect as compared to the primary factors previously discussed. Secondary factors include those effects which help optimize the bending process such as laser beam diameter, use of additional cooling, and increased beam-to-plate heat transfer coupling by the use of surface coatings. Secondary factors also include those effects which alter the bending process from normal conditions; these effects are: edge restraint, heating location, geometric constraint and plate prestrain.
Figure 5-41: Parametric Study Comparison - Constant vs. Variable Heat Input
All secondary bending factors will be discussed except laser beam diameter and plate prestrain. These factors should be examined by future investigators since there was insufficient time to fully examine these correlations.

5.1.2.1 Edge Restraint

As described in Chapter 3, the plastic flow of a heated material depends on the restraint of the cooler surrounding material. Therefore, if mechanical restraint can be imposed on one edge (i.e. clamping one edge of the plate) then this will provide additional resistance against which the heated metal can plastically flow. The net result should be increased bending past the centerline of the plate as the line heat pass gets progressively closer to the clamped edge. This was in fact observed. The results are tabulated in Table 5.2 and graphically shown in Figure 5.5. Figure 5.5 compares values for a plate with no boundary constraint and with boundary constraint. All plates were 12" x 12" (305mm x 305mm), A-36 mild steel, 1/2 inch thick. Laser power was 5 KW, plate travel speed was 8 ipm which gave a heat input of 37.5 KJ/in at the plate. On the far one-half of the plate away from the clamped edge, there is little or no effect of the clamping. As the line heat passes the plate's centerline, and gets successively closer to the clamped edge, the distortion increases. The plate is seeing a virtual increase in its planar dimensions due to the mechanical constraint. The data stops within 3.3 inches of the clamped edge due to the obstruction of the laser beam with the clamping device.

5.1.2.2 Heating Location

Bending is more pronounced as a line heat pass gets closer to a mechanically restrained edge. Alternatively, a line heat pass creates less bend as it approaches a free edge. As stated in Chapter 3, this is due to (1) the temperature differential decrease in the thickness direction, and (2) the plate material becomes too narrow to act as a heat sink in the plane dimension. This phenomenon was observed and is illustrated in Figure 5.6. All the test plates were 12" x 12" A-36 mild steel, 1/2 inch thick. Laser power was 5 KW and plate travel speed was 8 ipm. Plotted is all of the data.
Figure 5-5: Effects of Edge Restraint on Angular Distortion
Table 5-II: Effects of edge restraint, deflection measured by 2 techniques

<table>
<thead>
<tr>
<th>DISTANCE FROM PLATE'S EDGE (X) (in)</th>
<th>VERTICAL DISP. (Y) (in)</th>
<th>$\theta_f \left( \tan^{-1} \frac{Y}{X} \right)$</th>
<th>$\theta_f$ (LASER INTERFEROMETER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.79</td>
<td>0.0</td>
<td>0</td>
<td>.52</td>
</tr>
<tr>
<td>1.56</td>
<td>0.02</td>
<td>.72</td>
<td>.97</td>
</tr>
<tr>
<td>3.19</td>
<td>0.05</td>
<td>.89</td>
<td>1.16</td>
</tr>
<tr>
<td>4.76</td>
<td>0.09</td>
<td>1.08</td>
<td>1.06</td>
</tr>
<tr>
<td>5.90</td>
<td>0.125</td>
<td>1.21</td>
<td>1.13</td>
</tr>
<tr>
<td>6.70</td>
<td>0.16</td>
<td>1.37</td>
<td>1.06</td>
</tr>
<tr>
<td>7.48</td>
<td>0.17</td>
<td>1.30</td>
<td>1.24</td>
</tr>
<tr>
<td>8.27</td>
<td>0.19</td>
<td>1.32</td>
<td>1.14</td>
</tr>
<tr>
<td>8.66</td>
<td>0.19</td>
<td>1.25</td>
<td>1.20</td>
</tr>
</tbody>
</table>
taken from Series 2 and 3 experiments on the location of beam path versus distance from the plate edge. All distances represent the distance from the plate's edge to the beam's centerline. Even though some points were measured with a boundary constraint, they are all comparable since data was taken on the far one-half of the plate away from the clamped edge; the clamped edge has little or no effect in this part of the plate.

All deflections were created with a beam diameter of about 40 mm. The data points plot in a band of scatter of about .2 degrees. This can be primarily attributed to the inaccuracies of the measuring devices and techniques.

The results of Figure 5.6 show that as the center of the line heat pass gets closer to the plate's edge the distortion decreases. This relationship appears to be a function of the laser beam diameter. If the laser beam travels along, and parallel to, the edge of the plate the distortion is roughly 0.5 degrees. Now, if the beam center is moved a distance equal to the beam's diameter away from the plate's edge (in this case 40 mm), the distortion increases by a factor of 2; which will yield about 1.0 degree bend. The edge effect is less pronounced as the line heat pass gets successively closer to the plate's centerline. In fact, past 40 mm the curve rapidly flattens out from a value of 1.0 degree bend/pass to a constant 1.2 degree bend/pass.

5.1.2.3 Applied Cooling

The bending mechanism relies on the temperature differential in the through thickness direction. If the side opposite the irradiated surface (back side) is sufficiently cool, the heated metal will plastically flow and angular distortion will result. If the back side of the plate can transfer heat away efficiently, then the bending efficiency will increase. Our goal was to find the optimum heat transfer medium that would result in the most efficient distortion. All tests were conducted on 12 inch x 12 inch, 1/2 inch plate. 5 KW and 8 ipm plate travel speed was used as the heating input.

Table 5.3 lists the results of the experiment. The most efficient means to transfer heat away
<table>
<thead>
<tr>
<th>DATA POINT SYMBOL</th>
<th>BOUNDARY CONSTRAINT</th>
<th>MEASURING TECHNIQUE</th>
<th>DISTANCE FROM THE PLATE EDGE (mm)</th>
<th>$\theta_f$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>yes</td>
<td>Dial Gage</td>
<td>50, 82, 112</td>
<td>0.87, 1.20, 1.37</td>
</tr>
<tr>
<td>▲</td>
<td>yes</td>
<td>Dial Gage</td>
<td>20.3, 40.6, 81, 121, 150</td>
<td>0.72, 0.90, 1.08, 1.21</td>
</tr>
<tr>
<td>△</td>
<td>yes</td>
<td>Laser Inter.</td>
<td>20.3, 40.6, 81, 121, 150</td>
<td>0.52, 0.97, 1.16, 1.06, 1.13</td>
</tr>
<tr>
<td>○</td>
<td>no</td>
<td>Laser Inter.</td>
<td>41, 150, 94.8</td>
<td>0.95, 1.28, 1.04</td>
</tr>
</tbody>
</table>

**Figure 5-6:** Effects of Heating Location on Angular Distortion
was merely resting the steel test plate on the thick aluminum table used to move the test specimens underneath the laser beam. The high thermal diffusivity, \( \alpha \), of aluminum \((6.66 \times 10^{-5} \text{ m}^2/\text{S})\) and thermal conductivity, \( K \), \((194 \text{ w/m} \cdot \text{K at 200 degrees C})\) provided an efficient means to rapidly disperse the heat.

The results were surprising since we had anticipated that the water bath would transfer heat away more efficiently. The test plate rested in a water bath where the water immersed the plate up to one-half its' thickness. We had anticipated that the water would efficiently conduct heat away because of its high heat capacity, \( C_p \), \((4177 \text{ J/Kg} \cdot \text{K})\). However, when the beam traveled over the plate surface, the water underneath the plate would quickly boil which severely impaired the heat transfer. Moreover, we relied on natural convection which was inefficient in a stagnant waterbath.

In the same water bath, steel blocks were placed underneath the line heat pass on the backside of the plate (cooled method number 1). The bending efficiency increased due to the added conduction of heat by the steel supports. Steel has approximately \(1/4\) the thermal conductivity of aluminum, so even though the plate rested in a water bath, the heat transfer was not as efficient as cooling method number 5.

I speculate that the most efficient means to transfer heat would be to direct a water spray or water flow (forced water convection) on the backside of the plate while it's being heated. We did not have time for this experiment, but a forced water convection cooling system should be built and cooling experiments should be conducted by future investigators.

5.1.2.4 Geometric Constraint and Residual Stress

A given line heat pass will yield a unit bend per pass (excluding edge effects) depending on the plate thickness and input parameters. The effect of each line heat pass is additive. For example, if I want to bend a plate with 6 degrees of curvature, all I have to do is run 4 line heat passes, side by side, with each pass producing 1.5 degrees of curvature. However, a complication to
Table 5-III: Effects of cooling methods on angular distortion

<table>
<thead>
<tr>
<th>COOLING METHOD</th>
<th>$\theta_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Water bath, natural convection, with steel support underneath HAZ</td>
<td>1.16</td>
</tr>
<tr>
<td>#2 Water bath, natural convection, no steel support underneath HAZ</td>
<td>1.08</td>
</tr>
<tr>
<td>#3 Dry ice (plate rested on dry ice block)</td>
<td>1.11</td>
</tr>
<tr>
<td>#4 Forced air convection supplied to back side of plate</td>
<td>1.13</td>
</tr>
<tr>
<td>#5 Aluminum chill bar, plate rested on table bed (no air or water convection)</td>
<td>1.28</td>
</tr>
</tbody>
</table>
this simple procedure arises if passes are made one on top of another. The following scenario will help explain: If a flat plate is irradiated by a series of line heat passes, side by side, in the longitudinal direction, each pass will yield approximately 1.5 degrees of bend. Now, if on the same side of the plate a series of passes are run, side by side, in the transverse direction on top of the previously run longitudinal passes, each pass will now yield only 1.0 degrees per pass. This phenomenon was observed while forming a dish shape during the complex curvature studies of the series 2 experiments. For this experiment 10 inch by 10 inch, 1/2 thick, A-36 steel plate was used. A laser power of 7 KW was used with a plate travel speed of 12 ipm. The heat input per pas was 31.5 KJ/in (including 10% optical loss). Figure 5.7 lists the pass’ relation to the plate’s edge along with the corresponding angle deflection. All line heat passes in the transverse and longitudinal directions are at least one laser beam diameter away from the plate’s edge to reduce any edge effects.

The following explanation is offered for the deflection variation between the longitudinal and transverse passes:

1. Geometric Constraint. Once a flat plate is curved in the longitudinal direction, the imposed curvature offers a geometric constraint or resistance to bending in the transverse direction. This is analogous to an “I” beam which offers greater resistance to bending than a simple flat plate. In our case, the longitudinally curved plate is the geometrically more complex “I” beam. When the transverse passes try to bend this distorted shape, there is increased resistance to distortion.

2. Residual Stress. the initial longitudinal passes impart a tensile residual stress to the surface of the plate. Referring back to Figures 3.1 and 3.2, if tension is present, the elastic strain curve will be shifted up and the temperature rise to initiate plastic flow will be increased. This implies that additional heat is required to produce the same distortion per pass if additional passes are run on top of one another. In our case, the longitudinal passes produce a tensile residual stress. These passes were made with 31.5 KJ/in. If transverse passes are now run on the plate surface (that has tensile residual stress) with a heat input of 31.5 KJ/in, less distortion will be observed.

5.1.2.5 Beam Coupling

All of the plates during Series 1 and 2 experiments were coated with standard flat black spray paint to improve the coupling between the beam and the plate surface. Even though a heat input
<table>
<thead>
<tr>
<th>PASS</th>
<th>DISTANCE (X)</th>
<th>ELEVATION (Y)</th>
<th>$\theta_f (\tan^{-1}Y/X)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Longitudinal</td>
<td>45</td>
<td>.965</td>
<td>1.22</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>2.26</td>
<td>1.62</td>
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<tr>
<td>3</td>
<td>120</td>
<td>3.55</td>
<td>1.69</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>1.04</td>
<td>1.24</td>
</tr>
<tr>
<td>5</td>
<td>88</td>
<td>2.23</td>
<td>1.45</td>
</tr>
</tbody>
</table>

| 1 Transverse | 25           | .508          | 1.16                      |
| 2            | 65           | .94           | .83                       |
| 3            | 108          | 1.85          | 1.00                      |
| 4            | 25           | .508          | 1.16                      |
| 5            | 65           | .889          | .78                       |
| 6            | 108          | 2.11          | 1.15                      |

**NOTE:** Transverse passes were run on the same plate surface, after longitudinal passes were run.

**Figure 5-7:** Effect of Line Heating on a Previously Formed Plate
is specified at the plate surface, we do not know how much of the actual laser beam was absorbed and how much was reflected. All we can conclusively say is that given a heat input at the plate surface (based on laser power, plate travel speed and optical loss), and given that all specimens are sprayed with black spray paint, a certain plate deflection results. This deflection is reproducible, but we do not know the actual coupling between the beam and the plate. Therefore, limited experiments were conducted to see if there was a better coating that could be used which would provide better coupling between the beam and the plate. This improved coupling would increase the angular deflection per line heat pass.

The experimental standard to which an alternate coating would be compared is standard black spray paint. Experiments were conducted using 12 inch by 12 inch A-36 plate, 1/2 inch thick. All passes were made along the centerline of the plate using 5 KW and 8 inches per minute plate travel speed. Two surface coatings or preparations were compared to the standard of black spray paint. They were (1) "Aluma" Black A-15, a highly absorbing black spray coating, and (2) a bare sandblasted metal surface. The black spray paint produced 0.7 degree bend per pass where the "Aluma" Black produced 1.19 degree bend per pass. The bare sandblasted surface produced negligible distortion.

The highly absorbing black coating did increase the coupling between the beam and the plate. However, the cost of this coating may not justify the added deflection which is seen by its use. The sandblasted surface reflected almost 100% of the beam. In fact, the metal plate was cool to the touch directly after it was irradiated. Other more esoteric and expensive coatings such as tungsten, cupric-oxide, and manganese (which decrease beam reflectivity) were not tested.

5.1.3 Measurement Technique Comparison

Table 5.2 and Figure 5.6 tabulated results of heating location on angular distortion. For that study, one set of plates was measured with a dial indicator at the Naval Research Laboratory and then shipped to MIT where they were measured with a laser interferometer. This was done so each
measuring technique could be compared to one another to see if they were consistent and accurate. The angular deflections measured with a dial gage are denoted by a solid triangle in Figure 5.6; the same deflections measured with the laser interferometer are denoted by an open triangle. Both sets of points are connected to one another by a straight line.

The dial indicator showed no vertical deflection at 20.3 mm. 20.3 mm is the center of the beam that travelled parallel to and along the plate's edge. The laser interferometer, however, showed a curvature of .5 degrees. I attribute this inconsistency to the dial indicator's ability to measure radius of curvature (Figure 5.8, (top)). The radius of curvature is a gradual curvature caused by the diameter of the laser beam. Different beam diameters will yield different radii of curvatures even though the final distortion, $\Theta_f$ may be unaffected. Therefore, in Figure 5.8(bottom) when the beam travels along the edge of the plate, the dial indicator may not be able to detect a rise in point A due to a negative distortion of the plate, out of the X-plane. However, for an edge line heat pass, the laser interferometer can detect a variation in the radius of curvature by measuring a difference in fringe spacing. This ability and the fact that laser interferometer is a non-contacting method makes it a superior measuring technique. Despite this advantage, the laser interferometer at MIT has several limitations. Fringe spacing is manually measured by a ruler which gives this technique a range of errors of $\pm1$-.2 degrees depending on the skill of the operator. Also, the interferometer cannot measure distortion which exceeds 5-10 degrees. This instrument was adequate for measuring distortion caused by one line heat pass, however, large plates or plates with large distortions cannot be measured.

5.2 Complex Curvature Studies

The bending correlation studies provided us with a diverse amount of quantitative data on how laser line heating distorts low-carbon steel plates. Now that we had a better understanding of the bending process, we wanted to extend the application of laser line heating and show how this
Pass away from plate edge

Radius of curvature

Pass at plate edge

Radius of curvature

Figure 5-8: Radius of Curvature Produced by a Line Heat Pass
process could bend steel plate into complex shapes. We felt that our process was unique in that no other manufacturing system can bend flat steel plate (over 1/4 inch thick) into predetermined shapes with compound curvature. Our goal was to form a series of shapes that could be directly applied to the curvatures of a ship's hull. Our knowledge of the bending process allowed us to draw a schematic plan of the line heat sequence used to form each of these specific curvatures. From these schematic diagrams, the steel plate was formed in a controlled and accurate manner. The process was fast and efficient and required almost no skill by the operator. The predictability of this process allows easy reproduction of any shape that was formed.

The proposed shapes could be used by shipbuilders and designers to form complex shapes found in a ship's hull. Presently, Navy vessels and commercial tankers form complex shapes by welding together flat plate and plate with simple curvature. The shapes formed by laser line heating could improve current shipbuilding capabilities by forming a compound curvature out of one large plate. Several areas of a ship's hull where complex curvature might be used are (1) the stern area around a sonar dome or bulbous bow, and (2) the stern area around the propeller and transom areas. These areas require many different curvatures. Therefore, we have proposed (and formed) the following shapes that might possibly be applied:

1. *Sine Shape.* This is a plate with double curvature where one-half of the plate has a negative curvature and the other half of the plate has a positive curvature. The resulting form looks like a segment of a sine curve. This shape could be applied to a particular strake of a ship that is a transition plate from one curvature of a bilge radius to (a reverse curvature) of the flair at the bow.

2. *Dish Shape.* This plate is formed using longitudinal and transverse passes on the same side of the plate. The resulting shape resembles a dish or a bowl. This shape could be applied to the bulbous bow of a tanker, or possibly the nose of a submarine.

3. *Saddle Shape.* This plate is formed using longitudinal passes on one side of the plate and transverse passes on the opposite side of the plate. The resulting shape resembles a mathematical saddle point. This shape may be applied to a bulbous bow where orthogonal negative and positive curvature is required from the same plate. However, it was formed primarily to show the capabilities of this technique.

4. *Cone Segment 1.* This plate only has a simple curvature (bend in one direction) but it has a sharp "V" shape on the top edge of the plate and a smooth radius of curvature on the bottom edge. This shape can be used to transition from the stem of a ship to
the sonar dome or bulbous bow.

5. Cone Segment 2. This plate is a companion to Cone segment 1 however it has a smooth, but variable, radius of curvature on the top and bottom edge of the plate. This shape would be used in conjunction with Cone segment 1 for the sonar dome and bulbous bow.

6. Screw Shape 1. This plate is formed using diagonal passes on one-half of one surface and then using a mirror image of these passes on the other surface of the plate. The shape resembles a screw that can either have a left or right handed curvature. It can be applied to any strake around the bow or stern that needs to fair-in the general contours of the hull.

7. Screw Shape 2. This plate is formed by applying diagonal passes in one direction across one entire surface and then applying opposite diagonal passes (orthogonal to the initial passes) on the other surface. The resulting shape is similar to Screw shape 1, but the curvature is tighter and more pronounced. Again, this shape can be either left or right handed depending on the orientation of the diagonals.

Table 5.4 summarizes all the shapes that were formed giving plate size, plate type and heating input parameters. A total of 13 shapes were formed. The sine, dish and saddle shapes were formed during the Series 2 experiments in July 1984. For the Series 3 experiments in November 1984, we wanted to show the potential capabilities of laser line heating in a shipyard setting. Specifically, larger plate was used (18" x 24") to more closely resemble a plate used in a shipyard application. Also, screw and cone segments were formed using a high strength, quenched and tempered steel (A-710) to show the versatility of this process for different materials.

5 KW laser power was used for all shapes formed during the Series 3 experiments (all cone and screw shapes). We wanted to show that complex shapes could be formed using a relatively small (and more economically attractive) laser source. 8 inches per minute (for 1/2 inch plate) was chosen as the plate travel speed so the heat input would be less than 38 KJ/in. Reference 10 shows that for HY-80 and K-TEN80CF high strength steels, a single pass heat input of 33.75 KJ/in shows a beneficial effect of hardening (strengthening) while fracture toughness is maintained. Even though 5 KW and 8 ipm can effectively form the proposed shapes, higher power settings and faster plate travel speeds provide much more efficient bending per pass and greatly decrease production times for long plates.
Figures 5.9 through 5.16 show the arrangement of the heating lines used to form each shape. Appendix A contains photographs of the formed shapes, accompanied by a cover page describing appropriate input parameters.
Table 5-IV: Summary of complex shape experiments

<table>
<thead>
<tr>
<th>SHAPE</th>
<th>PLATE SIZE</th>
<th>THICKNESS</th>
<th>MATERIAL TYPE</th>
<th>POWER (kw)</th>
<th>TRAVEL SPEED (ipm)</th>
<th>HEAT INPUT (kJ/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine Curve</td>
<td>12&quot; x 12&quot;</td>
<td>1/2&quot;</td>
<td>A-36</td>
<td>6.3&quot;</td>
<td>12</td>
<td>31.5</td>
</tr>
<tr>
<td>Dish Shape</td>
<td>12&quot; x 12&quot;</td>
<td>1/2&quot;</td>
<td>A-36</td>
<td>4.5&quot;</td>
<td>8</td>
<td>33.75</td>
</tr>
<tr>
<td></td>
<td>10&quot; x 10&quot;</td>
<td>1/2&quot;</td>
<td>A-36</td>
<td>6.3&quot;</td>
<td>12</td>
<td>31.5</td>
</tr>
<tr>
<td>Saddle Shape</td>
<td>10&quot; x 10&quot;</td>
<td>1/2&quot;</td>
<td>A-36</td>
<td>6.3&quot;</td>
<td>12</td>
<td>31.5</td>
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<td>1/4&quot;</td>
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<td>A-710</td>
<td>5&quot;</td>
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Note: ① Laser power reflects kw input at the plate surface (after the 10% optical loss)
Figure 5-9: Sine Curve Shape
DISH SHAPE - WITH DIAGONAL PASSES

SOLID LINE: TOPSIDE PASS
DASHED LINE: PASS OPPOSITE SIDE

\[ \frac{1}{4}'' = 1'' \]

Figure 5-10: Dish Shape
Figure 5-11: Dish Shape
Figure 5-12: Saddle Shape
Figure 5-13: Cone Segment 1
Figure 5-14: Cone Segment 2
SOLID LINE: TOPSIDE PASS  
DASHED LINE: PASS OPPOSITE SIDE  

$1/4" = 1"$

SCREW #1 — (Either right or left handed curvature can be produced)

Figure 5-15: Screw Shape 1
SOLID LINE: TOPSIDE PASS
DASHED LINE: PASS OPPOSITE SIDE
\[ \frac{1}{4''} = 1 \]

Figure 5-16: Screw Shape 2
Chapter 6

Proposed Manufacturing Systems

Reference 16 outlines the work to be accomplished during Phase 2 which includes further metal forming experiments, material degradation studies, and proposing (and developing) a prototype laser metal forming manufacturing system to be built during Phase 3 (the third and final year of this project). The purpose of this chapter is to offer fundamental ideas that should be considered in developing a laser line heating manufacturing system, and, in so doing, serve as a starting point for Phase 2 researchers.

6.1 General Considerations

The ultimate goal of this project is to develop a manufacturing system that can form steel plates into complex shapes. The forming operation should be predictable, reproducible, and require little or no worker skill. Also, this system should be easily adapted to modern automation and control technologies.

To this end, a laser line heating system is proposed (Figure 6.1) which has the following salient characteristics: The system should be capable of forming large plates, on the order of 10 to 20 feet in any plane dimension, which are used in ship construction. These plates are typically on the order of 3/8 to 7/8 inch thick and are made from ordinary low carbon steel (A-36) or high strength steel (HY-80, A-710). The plates, because of their large size, will probably be formed one at a time as opposed to a batch or continuous manufacturing operation. The plates will be formed in a shop as opposed to on-site forming at the pier or drydock. The equipment needed to form these plates is relatively large and immobile. Therefore, the plates will be formed at the shop and then taken down to the drydock or pier where the hull or deck would be fabricated. The
equipment needed to form these plates includes an X-Y rotary table, Z-axis focusing head, chill-bar cooling, high-power industrial laser, helium-neon alignment laser, and a control system. A description of these components and some basic considerations are offered in the following paragraphs.

The plate should rest on a heavy-duty, rotary, X-Y direction milling machine table. This table would enable the plate to move, with three degrees of freedom, underneath the heat source which is fixed. The line heat beam should be supplied by a continuous wave, CO₂ laser that produces a beam with a wavelength of 10.6μm (in the infrared region). The requirement that the plate move underneath a fixed laser beam is solely a function of the stationary optics of a laser. If fiber optic (or some other technology) could be developed that would enable the laser beam to move without distorting its focal length and diameter, then a stationary workpiece and moveable beam configuration could be possible.

The laser beam strikes the plate with a fixed diameter. This beam diameter is a function of the fixed mirror in the optics and the distance the plate is from the mirror. As the plate deforms under the beam, the distance between the plate and the mirror will change. In fact, for a 10' x 10', 1/2 inch thick plate, five passes parallel to the plate's centerline can vertically deflect the edge of the plate almost one foot. The system must compensate for this change in focal length or the beam spot diameter will change. The beam spot diameter must remain constant since the angular deflection of the plate is a function of beam diameter. Therefore, the focusing head of the optics should be mounted on a vertical Z-axis table so the focusing spot of the beam can be adjusted. United Technologies (UT) has developed a similar system for use in laser welding (4). In addition to vertically adjusting focusing head, UT also installed a rotary coupling so that the angle of the focusing beam could be adjusted.

The rotary X-Y axis table bed should be capable of supplying cooling to the underneath (back) side of the plate. A proposed cooling arrangement would be to mount on the X-Y table an aluminum or copper chill bar through which forced air or water cooling could be supplied. The
chill bar would act as a heat sink and the water (or air) would aid heat transfer by supplying forced convection.

The plate should merely rest on the chill plate and not be suspended or clamped by any edge restraint. Unsymmetrical edge restraint would distort even bending by imposing mechanical resistance to the plastic flow of the heated metal.

The CO₂ laser should be capable of producing 5-6 KW of continuous power. Plates greater than (and equal to) 1/2 inch thick would be more efficiently bent by a more powerful laser (8-10 KW). The results of the parametric studies show that a higher laser power and faster plate travel speed can impart a greater angular distortion per line heat pass. Production time (time required to run a series of passes after the plate is on the X-Y table bed) using an 8-10 KW source can be decreased by threefold over a 5 KW source for plate thickness greater than and equal to 1/2 inch.

The CO₂ laser should be equipped with a low power helium neon laser for beam alignment. The CO₂ beam is invisible to the human eye, so a visible alignment beam is required to align the CO₂ beam and ascertain where the beam will strike the plate prior to a production run.

Every component of this system (high-power laser, X-Y table, focusing head Z-axis table, alignment laser and plate cooling system) can be controlled in one area as shown in Figure 6.1. The operator should be able to choose between manual or automatic control of the forming operation. A computer will control automatic forming by either an open loop, computer numerical control (CNC) or a closed loop, adaptive control system. Each of these automatic control systems will be discussed in detail later in this chapter. Reference 4 describes a laser welding system designed by United Technologies where the X-Y rotary table, and focusing head Z-axis table is controlled by servo motors through CNC. This was an open-loop control system where all axis motions were pre-determined and programmed by the operator. Figure 6.2 and 6.3 show an arrangement of a high-power CO₂ laser and control console. United Technologies makes either a 2 module, 6 KW laser or a 3 module, 9 KW laser that can be used for laser metal forming. Other
manufactures should be surveyed for the availability and price of similar power lasers. However, UT has working 6 and 9 KW laser material processing systems at Ford Motor Company, Pratt and Whitney Aircraft and Union Carbide (3). These systems could be easily modified to meet the requirements of metal forming.

6.2 Proposal 1 - Open Loop, NC System

A completely automatic metal forming system is to be proposed and developed during Phase 2 of this project. Masubuchi hopes to form an adaptive control system where a sensing device views the shape while it is being formed. The sensing device then signals back to a computer controller to vary system parameters (laser power, plate travel speed, etc.) until a particular shape is formed. This is called a closed loop control system and it requires absolutely no worker interaction to form a shape. This is a state-of-the-art technology and it will be discussed in detail in the next section of this chapter. However, the metal forming studies of Phase 1 show that laser line heating is a very predictable process; shapes are predetermined by running a series of known line heat passes which produces a known outcome. This characteristic of laser line heat makes it readily adapted to an advanced, but less state-of-the-art control technology called computer numerical control (CNC). CNC is an open loop system where a predetermined set of instructions are programmed to control system parameters. CNC accomplishes this by using a series of coded letters and numbers (similar to BASIC programming), which controls all system functions in a step-by-step manner. Control commands have a variety of functions which includes positioning the X-Y table in relation to the laser beam, controlling the speed and direction of travel of the table and even turning the laser beam and coolant on and off. In fact, all system functions needed to form a particular size plate into a predetermined shape is coded into NC language in a step-by-step format. This open loop control is shown in Figure 6.4. Worker skill is needed to program the computer in, an easy to learn, NC language. However, no skill is needed to form a particular shape. All line heat pass sequence and system instructions are predetermined and preprogrammed.
Figure 6-1: Proposed Laser Line Heating System
Despite these advantages, CNC is not as technologically advanced as closed loop adaptive control. There is no real-time control and feedback of system parameters to alter the forming process. For example, if the plate became overheated, which resulted in less bend per pass than was originally planned, there would be no way to feedback and control system parameters to produce more bend. However, in a predictable process, such as laser line heating, this capability may not be required; in which case an open loop CNC would be a satisfactory control technology. Several manufacturers (such as Allen-Bradley of the United States and Daewoo and Wotan of Korea) make CNC controllers which have been used since the 1970's in machine tools such as lathes and milling machines. These controllers could easily be adapted to a laser line heating system.

6.3 Proposal 2 - Closed Loop, Adaptive Control

Adaptive control (AC) is a closed loop control system where machining parameters are monitored and regulated by a computer. Parameters such as position or plate travel speed are compared with optimum process values by a feedback loop from a sensing device. If the process parameters do not match a set of preprogrammed values stored in the computer, the computer will then automatically manipulate the process so optimum forming will occur.

Reference 22 describes the principal developments in the adaptive control of machine tools. This article states that there are two types of AC systems used in machining operations:

1. Those using Adaptive Control for Optimization (ACO) which optimize a performance index (usually an economic function) subject to process and system constraints. ACO aims to optimize production times and production costs. An optimization algorithm would be used in the computer to find the "best" use of the manufacturing system for a given process.

2. Those using Adaptive Control with Constraints (ACC) which maximize forming parameters (e.g., feedrate or table velocity) subject to system constraints (e.g., maximum bend per given line heat pass).

All the discussion so far on adaptive control has been concerned with ACC systems. ACO systems have had problems in formulating realistic performance indices and in measuring the
INPUT REQUIRED SHAPE TO BE FORMED USING CODED NC LANGUAGE

SYSTEM CONTROL

SYSTEM COMPONENTS

\[ \text{CO}_2 \text{ LASER} \]

\[ \text{X-Y TABLE} \]

\[ \text{Z-AXIS FOCUSING HEAD} \]

\[ \text{TABLE COOLING} \]

WORKPIECE

FINAL PART

NC LOOP

(Feedback relating table position, focusing head height, etc., to system control)

**Figure 6-4:** Open Loop - CNC Laser Line Heating Control Schematic Diagram
required variables in the process environment. Consequently, ACO's application of optimizing economic functions has been limited mainly to a few grinding applications. We do not want to maximize economic functions in laser line heating, we only want to optimize the forming process so the system automatically forms a plate without worker interaction. Simply stated, we want the system to know if it's bending a 1/4 inch plate or a 1/2 inch plate and control the system parameters until a particular shape is achieved. This adaptive control application is of the ACC type. A simple block diagram of the closed loop system is proposed for laser metal forming in Figure 6.5.

A major impediment to the use of AC in modern manufacturing systems (such as cutting and milling operations) has been the development of accurate and reliable sensors to measure operating parameters. This is also the case in development of a laser metal forming system. The biggest hurdle in closing the loop of this control system will be developing a sensor which can "see" the bending process and then feedback to the computer for control. To complicate the problem further, what the sensing devices "see" is a transient process. The shape the plate assumes when the beam passes over the surface is not the final shape the plate will take after it cools. Therefore, the computer will have to interpret and account for transient behavior in its microprocessor.

6.3.1 Measuring Devices

There are two types of measuring devices that could be used; these are either contacting or non-contacting devices. Contacting devices include dial indicators, electro-mechanical transducers, strain gages, pneumatic transducers and hydraulic sensors. They all offer a means to measure plate distortion, but they have several inherent limitations. (1) Mechanical contact, they all must touch the surface to measure distortion. Not only is the instrument reading distorted by surface irregularities, but practical problems may arise for an instrument that is trying to measure a plate moving with three degrees of freedom, which is being irradiated by a high energy heat source. (2) Point contact - a contacting measuring device can only measure distortion of a plate at
Figure 6-5: Closed Loop - AC Laser Line Heating Control
Schematic Diagram
one point in one axis. However, laser line heating distorts plates in three dimensions which forms several different complex shapes. Therefore, full-field measuring is needed, which is capable of viewing the plate as one unit. Point contact by a mechanical device can measure an entire plate surface, but it does so by dividing, and measuring the device in many discrete elements.

**Non-contacting** devices are optical measuring instruments which measure displacement, rotation or velocity with sensors such as laser interferometers or holographic interferometers. These devices are usually full-field measuring devices, and usually do not have the limitations of point-contact mechanical measuring devices. A non-contacting optical device has the greatest potential for development in laser line heating.

The characteristics that are required of a measuring device used in laser line heating are: (1) 3-Dimensional. Not only must the device be capable of full-field measuring, it must also have the ability to measure distortion in three dimensions. (2) Large Measurement Range. The system must be insensitive to large displacements. 10-20 foot plates used in ship construction may have a final distortion on the order of several feet out of the original flat plane of the plate. The measuring device must be capable of measuring these large displacements without losing accuracy. (3) Real-Time Capability. An adaptive control system measures in-process parameters (in our case transient and final distortion). The measuring device must be equipped with an automatic means to view the plate while it is distorting.

6.3.1.1 Real-Time Sensing Devices

There are two measurement systems that have the greatest potential for development, and adaptation to a laser line heating system. Both of these systems are non-contacting, full-field optical measuring devices, that can measure 3-dimensional distortion in real-time. These systems are (1) Laser Distortion Monitoring System, and (2) Holographic Interferometry.

*Laser Distortion Monitoring System* is a device proposed under the auspices of Prof. Masubuchi for real time viewing of laser line heated plates. Figure 6.6 details the schematics of the
system. The device consists of a scanning box which contains a low power laser and a video camera. The following system description is extracted from reference 16.

The basic principle employed is a triangulation method that has been used for many years to measure distances. A laser power source is used as a source of light. A TV-camera is used to monitor the location of the point on the plate surface lit by the laser light. The laser light source should be rotated so that the point by the laser is placed at the center of the visual field of the camera. When the plate deforms, the point lit by the laser moves away from the center of the visual field of the camera. The amount of distortion can be determined by knowing the angle of rotation of the laser source in order to locate the laser lit point to the center of the visual field.

Proposed Alternative to the Laser Distortion Monitoring System. Electronically read interferometers are being used in industry in a wide range of applications such as calibrating micrometers in gage laboratories and checking longitudinal position of gantries in finishing machining of turbine cases (23,24). These interferometers are electronically read with accuracy on the order of .01μm. One such interferometer is manufactured by Hewlett-Packard. Figure 6.7 shows a schematic diagram for simple linear measurement (24).

This interferometer measures distortion by comparing the difference between two frequencies which strike the plate surface at one point. This point measuring device can be made into a full-field device by incorporating it as the laser used in the scanning device of Figure 6.6. The camera would not be required since the interferometer directly measures distance to the distorted plate surface.

The laser head contains a low power (.5mw) helium-neon laser that operates at a single frequency. This frequency is split into two discrete frequencies by applying an axial magnetic field to the beam. The field causes the lasing atoms to emit left-hand circularly polarized light at one frequency (f1) and a right-hand circularly polarized light at a second frequency (f2). Birefringent micaplates are used to convert the circular polarization into two linear components. The beam is now sampled by a pair of beam splitters arranged to cancel preferential reflections of f1 and f2, thus ensuring an accurate beam sample.

The two optical receivers in the laser head consist of a polarizer, a photodiode, a semi-custom
Figure 8-6: Schematic of Laser Distortion Monitoring System
Figure 6-7: Hewlett-Packard Laser Interferometer

integrated circuit and passive components. The two coaxial beams, f1 and f2, are orthogonally polarized and do not interfere. The polarizer is used to project both beams into a common axis halfway between the original axes so that they do not interfere. The photodiode converts the resulting intensity into variations in current.

The measurement display provides electronic read-out of the distortion measurement. The electronic signal could be fed-back to the computer controller. The computer would then compare this signal to a predetermined value and then alter heat input parameters until a particular distortion is achieved.

Holographic Interferometry is an entirely different alternative to the two scanning devices just described. Holographic interferometry has already been used to provide accurate, full-field, three-dimensional distortion measurement in large and small structures. The measuring device was
developed by Tan and Smith (21) to measure three-dimensional distortion in a milling machine.

Holography is the process of forming a true three-dimensional image by optical diffraction using laser light. The hologram is a complex diffraction grating, and is usually formed on fine grained photographic plate. It is constructed by the interference of an illuminating beam, and an undisturbed reference beam. Once the image is reconstructed by the reference beam, optical interference can occur through movement, or distortion of the illuminated object. The resulting interference fringes are contours of displacement.

There are two methods to obtain holographic fringe patterns: (i) frozen fringe and (2) real time. Frozen fringe is a technique where the final, or time averaged, displacement of the object is obtained. The hologram photographic plate is exposed twice before development. One exposure is before object displacement, and the other is afterwards. The hologram is then developed and the displacement fringes can be seen directly with the reconstructed image. The second technique is real time. With this technique, interference between the reconstructed image and the displaced object occurs after photographic development. Thus, a series of fringe patterns can be formed for different object displacements. To record the varying fringe patterns, a TV camera, monitor and video recorder are used, Figure 6.8 (21).

This real-time viewing arrangement can directly be applied to an adaptive control system. The image is viewed by the camera, which then translates the fringe image to the computer memory and storage. Once the plate image is stored into computer memory, the computer can make decisions as to the plate's orientation, distortion and dimensions. The computer compares this image to a preprogrammed image or constraint, and then varies the heating parameters until a certain distortion (fringe image) is obtained.

The fringe patterns produced by holography are merely a record of translation and rotation about any one of three coordinate axes. Displacements in three dimensions require viewing in three directions as shown in Figure 6.9 (21). The object surface deformation must be separated into
orthogonal in-plane, and out-of-plane deformations. To do so, three holograms must be made each at a different illumination and viewing angle. Figure 6.10 shows the three separate fringe patterns, taken at three different angles, necessary for three-dimensional analysis. These fringe photographs were taken of a milling machine deforming under static load (21).

In summary, each distortion sensing system has potential for development, and adaption to the closed loop adaptive control system. I believe the sensing device, and corresponding computer
software and control, will be the biggest hurdle in developing an automatic, closed loop, adaptive control system. These techniques that were presented should be a starting point for Phase 2 and Phase 3 investigators.
Figure 6-9: Optical system for Construction of 3 Separate Holograms

Figure 6-10: 3 Fringe Patterns taken from Different Directions for 3-D Analysis
Chapter 7
Computer Model

7.1 General Discussion

The bending correlation studies provided quantitative data on the effect laser line heating has on producing distortion in flat plates. This data shows that (1) each line heat pass produces a unit bend (excluding edge effects, mechanical restraint, etc.), and (2) the effect of each pass is essentially additive. Therefore, complex shapes can be easily produced by adding the angular distortion of a specific number of line heat passes in a specific orientation.

These results can be applied to a predictive computer model, which would allow a manufacturer to graphically determine a final complex shape, prior to forming the actual plate. The computer model uses the empirical results obtained in the bending correlation, and complex curvature studies to determine a specific shape. A costly numerical analysis, which predicts distortion based on a costly finite element analysis of thermal history and corresponding elastic-plastic strains, is not needed. The empirical data shows that the bending mechanism is a simple additive analysis of unit deflection per line heat pass. A finite element analysis would require a computer with significant speed, and storage capabilities, whereas the empirically based computer model developed here, requires the speed and storage capabilities of a PC or minicomputer.

I emphasize that this computer model is merely a design aid that can be used by a shipyard to predict final plate curvature. It does not provide any analysis of transient and residual, stresses and strains. An accurate finite element program should be developed which calculates residual stress, but it is not necessary for shape prediction.
7.2 Empirical Design Model

The computer program is written in BASIC and can be used on any IBM compatible personal computer. This program was developed and run on a Zenith, Z-100 personal computer, with a 10 megabyte Winchester drive, using "Z Basic", an IBM compatible BASIC language. The program is transferred and stored on a standard 3 1/2 inch floppy disk. The Zenith system is owned and maintained by MIT, Course 13A. I chose to write the program in BASIC, as opposed to FORTRAN, because it is a language that is easily followed and understood. The program can be run on the IBM compatible PCs, which are often user friendly and relatively inexpensive. Consequently, subsequent researchers should be able to follow, revise, or edit this program without much difficulty.

7.2.1 Program Specifics

Virtually every shape formed in the complex curvature studies were formed by a series of adjacent line heat passes run either horizontally, vertically, or diagonally. Similarly, this program graphically develops shapes by asking the user if he/she wants to run horizontal, vertical or diagonal passes on the top side, or back side of the plate. The program then runs a series of passes adjacent to one another, across the plate surface, based on the appropriate response of the user. In addition to heating the top side, and back side of the plate, the program can also run any number of horizontal and vertical passes, on the left or right 1/2 of the plate. The program can also run two different orientations of diagonal passes.

The program initially asks the user to input plate width, length and thickness. An X-Y array is then created based on the plate dimensions. After the appropriate horizontal, vertical, or diagonal passes are run, the computer prints out, and graphically shows each Z displacement deflection, corresponding to its X-Y coordinate. The program logic flow is found in Figures 7.1 through 7.3. The Z displacement is calculated by the additive effect of each line heat pass. The
same trigonometric relations used in Chapter 4 to calculate the plate displacements, using a dial indicator, is used in this program. Experimental data shows that for a given plate thickness and type, the Z deflection of the plate is related to a constant plate rotation per line heat pass. This rotation does not vary except for edge effects. Z deflection is controlled by a series of deflection equations in the program, Appendix B, which take the form:

\[ A(R,C) = A(R,C) + \text{(constant)}*((V-S)-(V-Q)) \]  \hspace{1cm} (7.1)

The constant can be changed to reflect different heating conditions, plate thickness, array spacing, etc. The following heating conditions, and plate rotations per pass are used in this program:

A. 1/4 inch plate. \( \Theta_f = 2.0 \) degrees per pass (heat input=18.75 KJ/in, laser power=5 KW, plate travel speed=8 ipm).

B. 1/2 inch plate. \( \Theta_f = 1.1 \) degrees per pass (heat input=37.5 KJ/in, laser power=5 KW, plate travel speed=8 ipm).

Edge effects (a decrease in deflection per pass as the beam approaches the plate's edge) are accounted for by starting, and ending the line heat pass, one beam diameter away from the plate's edge. There is no provision for mechanical constraint. Mechanical constraint would only introduce asymmetry in the bending process. All shapes that are produced by this program are symmetric.

Figure 7.4 is an example of the Z deflection array output. The array is meshed every 1 inch showing Z deflection in inches. The program is also graphics capable. After the program displays the Z deflection array, the program graphically produces the array in 3 dimensions. Figure 7.5 is offered for illustration.

### 7.2.2 Future Considerations

1. The program considers only one combination of laser power and plate travel speed, for each thickness. This is due to the initial proposition that a 5 KW laser power source would be used
to form the shapes. However, once a laser power source is decided upon in Phase 2, and a corresponding optimum power setting, and plate travel speed is determined for that power source, the deflection per pass can easily be altered, by changing one constant in the program, to reflect any heat input combination.

2. The beam diameter is not considered, since we only used a beam diameter of 1.5 inches for all metal forming studies. Once bending correlation studies are completed on beam spot size, the program can be easily amended to reflect a variable spot size. In fact, certain variables in the program are left as a function of the beam diameter, B, to facilitate inclusion of future spot size correlation studies.

3. Plate thickness is restricted to 1/4 inch and 1/2 inch. 3/4 inch and 1 inch plates are not considered in this program, since we only had parametric study results on the bending correlation between heat input, and plate thickness. There were no complex curvature studies conducted, which would verify the final outcome of Z-axis deflections in 3/4 inch and 1 inch thick plates. However, when these studies are completed, the program can be easily amended, by again, altering one constant in the deflection equations.

4. Material type is not accounted for, since there were no parametric studies conducted on HY-80 or A-710. Again, once these studies are conducted, the program can be easily amended by altering one constant in the deflection equations.

5. The program can calculate deflection for any size plate up to 2 feet by 2 feet. Diagonal passes are limited to square plates only. The program becomes laboriously slow for array dimensions greater than 20x20. If larger plates are used, the program will have to be altered to change the array spacing from every inch to every 2 or 3 inches.

6. The program does not take into account residual stress. Once further studies are completed in Phase 2, on the effect residual stress has on multiple passes, the program will have to account for the decreased bending of multi-layered passes.
7.2.3 Program Variables

The following is a list of more commonly used variables used in this program and their meanings:

\( A_1(R,C) \) - Cummulative array to which all horizontal, vertical, and diagonal passes add their contribution to deflection.

\( A(R,C), B(R,C) \) - Working arrays. Calculates deflection contribution of each horizontal, vertical and, diagonal set of passes.

\( R,C \) - Row and Column of all arrays.

\( WW, LL, TT \) - Plate width, length, and thickness (in inches).

\( X,Y \) - Array dimensions based on \( WW, LL, TT, \) and \( B \).

\( B \) - Laser beam diameter. Variable input to be added after laser spot size experiments of Phase 2.

\( E_1, E_2, F_1, \) etc. - Decision string variables. Input by user.

\( S, T, U, V, D, Q \) - Variables which initialize and control the size of a working array, prior to and during the running of passes.

\( P \) - Passes of laser line heat. Usually the overall controlling DO-LOOP variable for deflection calculations.

\( L, H \) - Highest and lowest value in the cummulative array. Used to normalize the plate to \( Z = 0 \).
Figure 7-1: Main Program - Logic Flow Chart
Figure 7-2: Horizontal and Vertical Pass Subroutine - Logic Flow Chart
Figure 7-2: Continued
Figure 7-8: Diagonal Pass Subroutine - Logic Flow Chart
Figure 7-3: Continued
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<td>0.22</td>
<td>0.26</td>
<td>0.30</td>
<td>0.34</td>
<td>0.38</td>
<td>0.42</td>
<td>0.46</td>
<td>0.50</td>
<td>0.54</td>
<td>0.58</td>
<td>0.62</td>
<td>0.66</td>
<td>0.70</td>
<td>0.74</td>
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<tr>
<td>-0.14</td>
<td>-0.17</td>
<td>-0.20</td>
<td>-0.23</td>
<td>-0.26</td>
<td>-0.30</td>
<td>-0.33</td>
<td>-0.36</td>
<td>-0.39</td>
<td>-0.42</td>
<td>-0.45</td>
<td>-0.48</td>
<td>-0.51</td>
<td>-0.54</td>
<td>-0.57</td>
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<td>-0.39</td>
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<td>-0.50</td>
<td>-0.53</td>
<td>-0.57</td>
<td>-0.60</td>
<td>-0.63</td>
<td>-0.66</td>
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<td>-0.32</td>
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<td>-0.55</td>
<td>-0.59</td>
<td>-0.64</td>
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<td>-0.76</td>
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<tr>
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<td>-0.25</td>
<td>-0.30</td>
<td>-0.35</td>
<td>-0.40</td>
<td>-0.45</td>
<td>-0.50</td>
<td>-0.55</td>
<td>-0.60</td>
<td>-0.65</td>
<td>-0.70</td>
<td>-0.75</td>
<td>-0.80</td>
<td>-0.85</td>
<td>-0.90</td>
</tr>
<tr>
<td>-0.09</td>
<td>-0.14</td>
<td>-0.19</td>
<td>-0.24</td>
<td>-0.29</td>
<td>-0.34</td>
<td>-0.39</td>
<td>-0.44</td>
<td>-0.49</td>
<td>-0.54</td>
<td>-0.59</td>
<td>-0.64</td>
<td>-0.69</td>
<td>-0.74</td>
<td>-0.79</td>
<td>-0.84</td>
</tr>
<tr>
<td>0.00</td>
<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
<td>0.19</td>
<td>0.24</td>
<td>0.29</td>
<td>0.34</td>
<td>0.39</td>
<td>0.44</td>
<td>0.49</td>
<td>0.54</td>
<td>0.59</td>
<td>0.64</td>
<td>0.69</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Figure 7.4: 2 Deflection Array of Laser Line Heated Plate

SHOWN ARE 2 DISPLACEMENTS PULLED EVERY 0.04 INCH
Figure 7-5: Graphics Display of Laser Line Heated Plate
Chapter 8
Conclusion

8.1 Bending Correlation Studies

8.1.1 Primary Bending Factors

1. For a given plate thickness, there is an optimum combination of heat input and plate travel speed, $P/\sqrt{V}$, that yields a maximum bend per line heat pass. Alternatively stated, the amount of angular distortion increases as the heat input increases, until a maximum efficiency is reached.

2. For a given value of heat input, the amount of angular distortion increases as the plated thickness decreases. A laser line heat pass, using 65 KJ/in, can impart up to 0.8 degrees bend in a 1 inch thick, mild steel plate. Similarly, a line heat pass, of 19 KJ/in, can impart up to 2 degrees of bend in a 1/4 inch thick, mild steel plate.

3. An upper bound is reached when the parameter $P/\sqrt{V}$ produces a heat input that exceeds 65 KJ/in. Plates $> 3/4$ inch thick cannot reach maximum bending efficiency, due to surface melting and material degradation.

4. Generally, higher plate travel speed and laser power result in greater bend per line heat pass, and faster production time. For a given constant $P/\sqrt{V}$, a higher laser power and plate travel speed will yield a greater bend, than a lower power and plate travel speed.

8.1.2 Secondary Bending Factors

1. Edge Restraint. As a line heat pass, passes the plate's centerline, and gets successively closer to a clamped edge, angular distortion per pass increases. The plate sees a virtual increase in
it's plane dimension due to the mechanical restraint.

2. Heating Location. A line heat pass creates less bend as it approaches a free edge. This phenomenon is due to (1) the temperature differential decreases in the thickness direction, and (2) the plate material between the line heat pass, and the free edge, becomes too narrow to act as a heat sink.

3. Applied Cooling. Cooling the back side of the plate during a line heat pass increases the through thickness temperature differential, thereby increasing bending efficiency. The most efficient means of cooling the plate is by having it rest on an aluminum or copper chill bar, with forced air or water cooling.

4. Residual Stress. If a plate surface has tensile residual stress, from previously run line heat passes, any additional line heat pass, on the same surface, will produce less bend per pass.

5. Surface Coating. Plates must be coated with a standard black spray paint prior to heating. A highly absorbant black coating produces a somewhat better beam coupling, but the increased coupling does not justify the added cost.

8.2 Complex Curvature Studies

Many complex shapes have been produced using laser line heat including sine curve shape, dish shape, saddle shape, cone segments, and various screw shapes. These shapes can easily be formed, and predicted. A known series of passes will produce a known outcome, since each pass produces a unit bend per pass.

Shapes were formed using both mild steel, and high-strength steel (A-710). For a given heat input and plate travel speed, the bend produced with high-strength steel was approximately 75% of the bend produced with mild steel.
8.3 Recommendations

Based on the findings of Phase 1, the following recommendations are proposed:

1. The parametric study for 1/2 inch thick mild steel plate, should should be conducted again with constantly increasing heat input, along with constantly increasing P/\sqrt{V}.

2. A parametric study for 3/8 inch thick mild steel should be conducted. There is a wide range of values between 1/4 inch and 1/2 inch thick plates.

3. The parametric study for 1/4 inch thick mild steel, at 19 KJ/in, should be verified. There is a sharp drop-off in bending efficiency after 19 KJ/in.

4. Parametric studies should be conducted on high-strength, HY-80 or A-710, quenched and tempered steels. Thicknesses should include 1/4, 3/8, 1/2, 5/8, 3/4, and 1 inch thick plates.

5. A series of experiments should be conducted on the effect of laser spot size versus degree bend per pass. Spot sizes ranging from 0.5 inches to 2.5 inches should be used.

6. The effect of residual stress (multiple passes) should be examined further. A unit bend per pass hypothesis is not valid when passes are run on top of one another.
References


20. Rothman, R.L., *Effect of Temperature and Strain upon Ship Steels*, Battelle Memorial Institute, Columbus, Ohio, SSC-235, March 1973


Appendix A

Photographs: Complex Curvature Study
SINE SHAPE

PLATE SIZE
12in X 12in

PLATE THICKNESS
1/2 inch

MATERIAL
A-36 Mild Steel

POWER INPUT
6.3 KW

PLATE TRAVEL SPEED
13 lpm

HEAT INPUT
31.5 KJ/in

BEAM DIAMETER
1.5 in (38.1 mm)

NUMBER OF PASSES
8 (4 each side)
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Size</td>
<td>10 in X 10 in</td>
</tr>
<tr>
<td>Plate Thickness</td>
<td>1/2 inch</td>
</tr>
<tr>
<td>Material</td>
<td>A-36 Mild Steel</td>
</tr>
<tr>
<td>Power Input</td>
<td>6.3 KW</td>
</tr>
<tr>
<td>Plate Travel Speed</td>
<td>12 ipm</td>
</tr>
<tr>
<td>Heat Input</td>
<td>31.5 KJ/in</td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>1.5 in (38.1 mm)</td>
</tr>
<tr>
<td>Number of Passes</td>
<td>30 (6 long., 6 trans., 9 diag., 9 dl)</td>
</tr>
</tbody>
</table>
DISH SHAPE

PLATE SIZE
12in X 12in

PLATE THICKNESS
1/2 inch

MATERIAL
A-36 Mild Steel

POWER INPUT
4.5 KW

PLATE TRAVEL SPEED
8 lpm

HEAT INPUT
33.75 KJ/in

BEAM DIAMETER
1.5 in (38.1 mm)

NUMBER OF PASSES
10 (9 trans., 10 long.)
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLATE SIZE</td>
<td>10 in X 10 in</td>
</tr>
<tr>
<td>PLATE THICKNESS</td>
<td>1/3 inch</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>A-36 Mild Steel</td>
</tr>
<tr>
<td>POWER INPUT</td>
<td>6.3 KW</td>
</tr>
<tr>
<td>PLATE TRAVEL SPEED</td>
<td>12 lpm</td>
</tr>
<tr>
<td>HEAT INPUT</td>
<td>31.5 KJ/in</td>
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<tr>
<td>BEAM DIAMETER</td>
<td>1.5 in (38.1 mm)</td>
</tr>
<tr>
<td>NUMBER OF PASSES</td>
<td>32 (16 long. top, 16 trans)</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Plate Size</td>
<td>18in X 24in</td>
</tr>
<tr>
<td>Plate Thickness</td>
<td>1/4 inch</td>
</tr>
<tr>
<td>Material</td>
<td>A-36 Mild Steel</td>
</tr>
<tr>
<td>Power Input</td>
<td>5.0 KW</td>
</tr>
<tr>
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<td>10 lpm</td>
</tr>
<tr>
<td>Heat Input</td>
<td>18.75 KJ/ln</td>
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<tr>
<td>Beam Diameter</td>
<td>1 5/8 in (43.1 mm)</td>
</tr>
<tr>
<td>Number of Passes</td>
<td>7 (topside only)</td>
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</table>
PLATE SIZE
18in X 34in

PLATE THICKNESS
1/3 inch

MATERIAL
A-36 Mild Steel

POWER INPUT
5.0 KW

PLATE TRAVEL SPEED
8 lpm

HEAT INPUT
37.5 KJ/in

BEAM DIAMETER
1 5/8 in (43.1 mm)

NUMBER OF PASSES
7 (topside only)
PLATE SIZE
18 in X 24 in

PLATE THICKNESS
1/4 inch

MATERIAL
A-36 Mild Steel

POWER INPUT
5.0 kW

PLATE TRAVEL SPEED
10 ipm

HEAT INPUT
18.75 KJ/in

BEAM DIAMETER
1 5/8 in (43.1 mm)

NUMBER OF PASSES
13 (topside only)
## Cone Segment 2

<table>
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<th>Specification</th>
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<tr>
<td>Plate Thickness</td>
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<tr>
<td>Material</td>
<td>A-36 Mild Steel</td>
</tr>
<tr>
<td>Power Input</td>
<td>5.0 kW</td>
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<tr>
<td>Plate Travel Speed</td>
<td>8 lpm</td>
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<tr>
<td>Heat Input</td>
<td>37.5 KJ/ln</td>
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<tr>
<td>Beam Diameter</td>
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</tr>
<tr>
<td>Number of Passes</td>
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</table>
PLATE SIZE
18in X 24in

PLATE THICKNESS
1/3 inch

MATERIAL
A-710 HSLA

POWER INPUT
5.0 KW

PLATE TRAVEL SPEED
8 lpm

HEAT INPUT
37.5 KJ/in

BEAM DIAMETER
1 5/8 in (43.1 mm)

NUMBER OF PASSES
13 (topside only)
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PLATE SIZE</strong></td>
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<tr>
<td><strong>PLATE THICKNESS</strong></td>
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<tr>
<td><strong>MATERIAL</strong></td>
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<td><strong>POWER INPUT</strong></td>
<td>5.0 KW</td>
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<tr>
<td><strong>PLATE TRAVEL SPEED</strong></td>
<td>8 lpm</td>
</tr>
<tr>
<td><strong>HEAT INPUT</strong></td>
<td>37.5 KJ/in</td>
</tr>
<tr>
<td><strong>BEAM DIAMETER</strong></td>
<td>1 5/8 in (43.1 mm)</td>
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<tr>
<td><strong>NUMBER OF PASSES</strong></td>
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### SCREW SHAPE 2

<table>
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<td>PLATE SIZE</td>
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<tr>
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<td>1/4 inch</td>
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<tr>
<td>NUMBER OF PASSES</td>
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### SCREW SHAPE 2

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<td>PLATE THICKNESS</td>
<td>1/2 inch</td>
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<td>POWER INPUT</td>
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<td>PLATE TRAVEL SPEED</td>
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<tr>
<td>HEAT INPUT</td>
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<tr>
<td>BEAM DIAMETER</td>
<td>1 5/8 in (43.1 mm)</td>
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<tr>
<td>NUMBER OF Passes</td>
<td>34 (17 top side, 17 back side)</td>
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</tbody>
</table>
Appendix B

Laser Line Heating Computer Program
10 REM******************************************************************************
20 REM******************************************************************************
30 REM LASER METAL FORMING PROGRAM
40 REM******************************************************************************
50 REM******************************************************************************
60 DIM A1(25,25),A2(25,25),B(25,25),R(4,4)
70 KEY OFF
80 CLS
90 RX=RX+80:RY=RY+85:RZ=RZ-3
100 INPUT "ENTER PLATE DEFLECTION SCALE FACTOR (eg 10):";SZ
110 SX=SZ:SY=8
120 PI=3.14159
130 RX=RX*3.14159/180
140 RY=RY*3.14159/180
150 RZ=RZ*3.14159/180
160 R(1,1)=COS(RY)*COS(RZ)
170 R(1,2)=COS(RY)*SIN(RZ)
180 R(1,3)=-SIN(RY)
190 R(1,4)=0
200 R(2,1)=COS(RX)*(-SIN(RZ))+SIN(RX)*SIN(RY)*COS(RZ)
210 R(2,2)=COS(RX)*COS(RZ)+SIN(RX)*SIN(RY)*SIN(RZ)
220 R(2,3)=SIN(RX)*COS(RY)
230 R(2,4)=0
240 R(3,1)=(-SIN(RX))*(-SIN(RZ))+COS(RX)*COS(RZ)
250 R(3,2)=-SIN(RX)*COS(RZ)+COS(RX)*SIN(RY)*SIN(RZ)
260 R(3,3)=COS(RX)*COS(RY)
270 R(3,4)=0:R(4,1)=0:R(4,2)=0:R(4,3)=0:R(4,4)=1
280 C(1,1)=SX*R(1,1)
290 C(1,2)=SX*R(1,2)
300 C(1,3)=SX*R(1,3)
310 C(1,4)=0
320 C(2,1)=SY*R(2,1)
330 C(2,2)=SY*R(2,2)
340 C(2,3)=SY*R(2,3)
350 C(2,4)=0
360 C(3,1)=SZ*R(3,1)
370 C(3,2)=SZ*R(3,2)
380 C(3,3)=SZ*R(3,3)
390 C(3,4)=0
400 C(4,1)=0:C(4,2)=0:C(4,3)=0:C(4,4)=1
410 CLS
420 PRINT "INPUT PLATE THICKNESS (.25 , .5)"
430 INPUT TT
440 PRINT "INPUT PLATE LENGTH (INCHES)"
450 INPUT LL
460 PRINT "INPUT PLATE WIDTH (INCHES)"
470 INPUT WW
480 REM THIS LINE CAN BE EASILY MODIFIED FOR VARIABLE BEAM
490 LET B=1
500 REM CALCULATE THE ARRAY SIZE BASED ON L,W,B
510 LET Y=INT(LL/B)+1
520 LET X=INT(W/W)+1
530 REM LOAD ZEROS INTO ARRAY AND INITIALIZE
540 FOR R=1 TO Y
550 FOR C=1 TO X
560 LET A(R,C)=0
570 NEXT C
580 NEXT R
590 REM******************************************************************************
600 REM CALCULATE EITHER HORIZONTAL OR VERTICAL PASSES
610 REM******************************************************************************
620 CLS
630 PRINT "DO YOU WANT TO RUN HORIZONTAL PASSES? (Y/N)"
640 INPUT F$;
650 IF F$="Y" THEN 670
660 GOTO 710
670 GOSUB 3100
680 PRINT "DO YOU WANT TO RUN ANOTHER HORIZONTAL PASS? (Y/N)"
690 INPUT G$;
700 IF G$="Y" THEN 670
710 CLS
720 PRINT "DO YOU WANT TO RUN VERTICAL PASSES? (Y/N)"
730 INPUT M$;
740 IF M$="Y" THEN 760
750 GOTO 810
760 GOSUB 1430
770 PRINT "DO YOU WANT TO RUN ANOTHER VERTICAL PASS? (Y/N)"
780 INPUT N$;
790 IF N$="Y" THEN 760
800 REM******************************************************************************
810 REM CALCULATE DIAGONAL PASSES
820 REM******************************************************************************
830 CLS
840 PRINT "DO YOU WANT TO RUN DIAGONAL PASSES? (Y/N)"
850 INPUT P$;
860 IF P$="Y" THEN 880
870 GOTO 940
880 GOSUB 4770
890 PRINT "DO YOU WANT TO RUN ANOTHER DIAGONAL PASS? (Y/N)"
900 INPUT Q$;
910 IF Q$="Y" THEN 880
REM***                                      
REM PRINT OUT FINAL DISPLACEMENTS           
REM***                                      
FOR R=1 TO Y                                
FOR C=1 TO X                                
PRINT USING "###.###"; A1(R,C);             
NEXT C                                      
PRINT                                      
1000 NEXT R                                
1010 PRINT                                  
1020 PRINT "SHOWN ARE 2-DISPLACEMENTS MESHEd EVERY INCH" 
1030 PRINT "DO YOU WANT HARD COPY OF THIS? (Y/N)" 
1040 INPUT R$                              
1050 IF R$="Y" THEN 1070                   
1060 GOTO 1150                             
1070 FOR R=1 TO Y                          
1080 FOR C=1 TO X                          
1090 LPRINT USING "###.###"; A1(R,C);      
1100 NEXT C                                
1110 LPRINT                                
1120 NEXT R                                
1130 LPRINT "SHOWN ARE 7-DISPLACEMENTS MESHEd EVERY INCH" 
1140 CLS                                    
1150 XO=45:YO=100:ZO=0:FF=2.5:CLS           
1160 FOR R=1 TO Y                          
1170 FOR C=1 TO X                          
1180 GOSUB 1320                             
1190 IF C=1 THEN PSET(XPLOT,YPLOT),0       
1200 LINE - (XPLOT,YPLOT),2                 
1210 NEXT C                                
1220 NEXT R                                
1230 FOR C=1 TO X                          
1240 FOR R=1 TO Y                          
1250 GOSUB 1320                             
1260 IF R=1 THEN PSET(XPLOT,YPLOT),0       
1270 LINE - (XPLOT,YPLOT),6                 
1280 NEXT R                                
1290 NEXT C                                
1300 END
1310 REM------SUBROUTINE TO CALCULATE X, Y, AND Z POINTS ------
1320 XVAL = (100/LL)*(C-1)
1330 YVAL = (35/WW)*(R-1)
1340 ZVAL = SZA1(R,C)
1350 XR=XVAL*C(1,1)+YVAL*C(2,1)+ZVAL*C(3,1)+C(4,1)
1360 YR=XVAL*C(1,2)+YVAL*C(2,2)+ZVAL*C(3,2)+C(4,2)
1370 ZR=XVAL*C(1,3)+YVAL*C(2,3)+ZVAL*C(3,3)+C(4,3)
1380 XPLOT=X0+XR
1390 YPLOT=Y0+YR
1400 ZPLOT=Z0+ZR
1410 RETURN
1420 REM---------------------------------------------------------------
1430 REM SUBROUTINE FOR VERTICAL (COLUMN) PASSES
1440 REM---------------------------------------------------------------
1450 REM INITIALIZE WORKING ARRAYS TO ZERO
1460 FOR R=1 TO Y
1470 FOR C=1 TO X
1480 LET A(R,C)=0
1490 LET B(R,C)=0
1500 NEXT C
1510 NEXT R
1520 REM************************************************************************
1530 REM HEAT EITHER THE WHOLE SIDE OR 1/2 THE SIDE
1540 REM************************************************************************
1550 PRINT "DO YOU WANT TO HEAT THE ENTIRE PLATE SIDE? (Y/N)"
1560 INPUT E$
1570 IF E$="Y" THEN 1810
1580 REM************************************************************************
1590 REM HEAT LEFT 1/2 OR RIGHT 1/2
1600 REM************************************************************************
1610 LET LR=2
1620 PRINT "DO YOU WANT TO HEAT THE LEFT SIDE OR RIGHT SIDE?"
1630 INPUT E1$
1640 IF E1$="LS" THEN 1720
1650 LET T1=INT((X-1)/2+1)
1660 LET S=INT((X-1)/2)+2
1670 LET T=INT((X-1)/2)+2
1680 LET U=X-1
1690 LET V=X
1700 GOTO 1900
1710 REM************************************************************************
1720 REM LEFT 1/2
1730 REM************************************************************************
1740 LET T1=1
1750 LET S=2
1760 LET T=2
1770 LET U=INT((X-1)/2)
1780 LET V=INT((X-1)/2)+1
1790 GOTO 1900
1800 REM************************************************************************
1810 REM HEAT ENTIRE PLATE SIDE
1820 REM************************************************************************
1830 LET LR=1
1840 LET T1=1
1850 LET S=2
1860 LET T=2
1870 LET U=X-1
1880 LET V=X
1890 REM**************************************************************************
1895 REM HEAT TOP SIDE OR BACK SIDE (entire, left 1/2, right 1/2)
1900 REM**************************************************************************
1905 PRINT "DO YOU WANT TO HEAT THE TOP SIDE OR BACK SIDE?"
1910 INPUT E2$
1915 PRINT "crunch, crunch....."
1920 IF E2$="BS" THEN 2240
1925 REM**************************************************************************
1930 REM TOPSIDE CALCS
1935 REM**************************************************************************
1940 IF E2$="LS" THEN 2120
1945 FOR P=T TO U STEP 2
1950 LET Q=S
1955 FOR C=P TO V
1960 FOR R=1 TO Y
1965 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*LR
1970 NEXT R
1975 LET Q=Q+1
1980 NEXT C
1985 LET S=S+2
1990 NEXT P
2000 IF E2$="RS" THEN 2740
2005 GOTO 2510
2010 FOR P=U TO T STEP -2
2015 LET Q=S
2020 FOR C=P TO 1 STEP -1
2025 FOR R=1 TO Y
2030 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*LR
2035 NEXT R
2040 LET Q=Q+1
2045 NEXT C
2050 LET S=S+2
2055 NEXT P
2060 GOTO 2740
2230 REM*********************************************************************
2240 REM BACK SIDE CALCS
2250 REM*********************************************************************
2260 IF E1$="LS" THEN 2390
2270 FOR P=1 TO U STEP 2
2280 LET Q=S
2290 FOR C=P TO V
2300 FOR R=1 TO Y
2310 LET A(R,C)=A(R,C)+B.999999E-03*((V-S)-(V-Q))*(1/TT)*(-1)*LR
2320 NEXT R
2330 LET Q=Q+1
2340 NEXT C
2350 LET S=S+2
2360 NEXT P
2370 IF E1$="RS" THEN 2740
2380 GOTO 2510
2390 FOR F=U TO T STEP -2
2400 LET Q=S
2410 FOR C=F TO 1 STEP -1
2420 FOR R=1 TO Y
2430 LET A(R,C)=A(R,C)+B.999999E-03*((V-S)-(V-Q))*(1/TT)*(-1)*LR
2440 NEXT R
2450 LET Q=Q+1
2460 NEXT C
2470 LET S=S+2
2480 NEXT P
2490 GOTO 2740
2500 REM*********************************************************************
2510 REM REVERSE MATRIX
2520 REM*********************************************************************
2530 FOR C=T1 TO V
2540 FOR R=1 TO Y
2550 LET B(R,C)=A(R,C)
2560 NEXT R
2570 NEXT C
2580 LET Q=V
2590 FOR C=T1 TO V
2600 FOR R=1 TO Y
2610 LET B(R,C)=A(R,Q)
2620 NEXT R
2630 LET Q=Q-1
2640 NEXT C
2650 REM*********************************************************************
2660 REM NOW ADD 2 ARRAYS
2670 REM*********************************************************************
2680 FOR R=1 TO Y
2690 FOR C=1 TO X
2700 LET A(R,C)=A(R,C)+B(R,C)
2710 NEXT C
2720 NEXT R
REM FIND LOWEST VALUE IN ARRAY
LET H=A(1,1)
LET L=A(1,1)
FOR I=2 TO X
IF L<A(1,I) THEN 2810
LET L=A(1,I)
2810 IF H>A(1,I) THEN 2830
LET H=A(1,I)
NEXT I
PRINT "H=",H,"L=",L
REM NORMALIZE ARRAY
REM ADD WORKING ARRAY A TO CUMMULATIVE ARRAY A1
FOR R=1 TO Y
FOR C=1 TO X
A(R,C)=A(R,C)-L
NEXT C
NEXT R
GOTO 3010
FOR R=1 TO Y
FOR C=1 TO X
A1(R,C)=A1(R,C)+A(R,C)
NEXT C
NEXT R
RETURN
3090 athom-------------------------------
3100 REM SUBROUTINE FOR HORIZONTAL (ROW) PASSES
3110 REM-------------------------------
3120 REM INITIALIZE WORKING ARRAYS TO ZERO
3130 FOR R=1 TO Y
3140 FOR C=1 TO X
3150 LET A(R,C)=0
3160 LET B(R,C)=0
3170 NEXT C
3180 NEXT R
3190 REM*************************************************************************
3200 REM HEAT EITHER THE ENTIRE SIDE OR 1/2 THE SIDE
3210 REM*************************************************************************
3220 PRINT "DO YOU WANT TO HEAT THE ENTIRE PLATE SIDE? (Y/N)"
3230 INPUT E$
3240 IF E$="Y" THEN 3480
3250 REM*************************************************************************
3260 REM HEAT LEFT 1/2 OR RIGHT 1/2
3270 REM*************************************************************************
3280 LET LR=2
3290 PRINT "DO YOU WANT TO HEAT THE LEFT SIDE OR THE RIGHT SIDE?"
3300 INPUT E1$
3310 IF E1$="LS" THEN 3390
3320 LET T1=INT((Y-1)/2+1)
3330 LET S=INT((Y-1)/2)+2
3340 LET T=INT((Y-1)/2)+2
3350 LET U=Y-1
3360 LET V=Y
3370 GOTO 3570
3380 REM*************************************************************************
3390 REM LEFT 1/2
3400 REM*************************************************************************
3410 LET T1=1
3420 LET S=2
3430 LET T=2
3440 LET U=INT((Y-1)/2)
3450 LET V=INT((Y-1)/2+1)
3460 GOTO 3570
3470 REM*************************************************************************
3480 REM HEAT ENTIRE PLATE SIDE
3490 REM*************************************************************************
3500 LET LR=1
3510 LET T1=1
3520 LET S=2
3530 LET T=2
3540 LET U=Y-1
3550 LET V=Y
3560 REM*******************************************************************************
3570 REM HEAT TOP SIDE OR BACK SIDE
3580 REM*******************************************************************************
3590 PRINT "DO YOU WANT TO HEAT THE TOP SIDE OR BACK SIDE": CT5/BS
3600 INPUT E2$
3610 PRINT "crunch, crunch....."
3620 IF E2$="BS" THEN 3910
3630 REM*******************************************************************************
3640 REM TOPSIDE CALCS
3650 REM*******************************************************************************
3660 IF E1$="LS" THEN 3790
3670 FOR P=1 TO U STEP 2
3680 LET Q=S
3690 FOR R=P TO V
3700 FOR C=1 TO X
3710 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*LR
3720 NEXT C
3730 LET Q=Q+1
3740 NEXT R
3750 LET S=S+2
3760 NEXT P
3770 IF E1$="RS" THEN 4410
3780 GOTO 4180
3790 FOR P=U TO T STEP -2
3800 LET Q=S
3810 FOR R=P TO 1 STEP -1
3820 FOR C=1 TO X
3830 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*LR
3840 NEXT C
3850 LET Q=Q+1
3860 NEXT R
3870 LET S=S+2
3880 NEXT P
3890 GOTO 4410
3500 REM******************************************************************************
3510 REM BACKSIDE CALCS
3520 REM******************************************************************************
3530 IF E1$="LS" THEN 4060
3540 FOR P=T TO U STEP 2
3550 LET Q=S
3560 FOR R=P TO V
3570 FOR C=1 TO X
3580 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*(-1)*LR
3590 NEXT C
3600 LET Q=Q+1
3610 NEXT R
3620 LET S=S+2
3630 NEXT P
3640 IF E1$="RS" THEN 4410
3650 GOTO 4180
3660 FOR P=U TO T STEP -2
3670 LET Q=S
3680 FOR R=P TO 1 STEP -1
3690 FOR C=1 TO X
3700 LET A(R,C)=A(R,C)+8.999999E-03*((V-S)-(V-Q))*(1/TT)*(-1)*LR
3710 NEXT C
3720 LET Q=Q+1
3730 NEXT R
3740 LET S=S+2
3750 NEXT P
3760 GOTO 4410
4170 REM******************************************************************************
4180 REM REVERSE MATRIX
4190 REM******************************************************************************
4200 FOR R=T1 TO V
4210 FOR C=1 TO X
4220 LET B(R,C)=A(R,C)
4230 NEXT C
4240 NEXT R
4250 LET Q=Y
4260 FOR R=T1 TO V
4270 FOR C=1 TO X
4280 LET B(R,C)=A(Q,C)
4290 NEXT C
4300 LET Q=Q-1
4310 NEXT R
4320 REM******************************************************************************
4330 REM NOW ADD TWO ARRAYS
4340 REM******************************************************************************
4350 FOR R=1 TO Y
4360 FOR C=1 TO X
4370 LET A(R,C)=A(R,C)+B(R,C)
4380 NEXT C
4390 NEXT R
4400 REM************************************************************************
4410 REM FIND LOWEST/HIGHEST VALUE IN ARRAY
4420 REM************************************************************************
4430 LET H=A(1,1)
4440 LET L=A(1,1)
4450 FOR I=2 TO Y
4460 IF L<A(I,1) THEN 4480
4470 LET L=A(I,1)
4480 IF H>A(I,1) THEN 4500
4490 LET H=A(I,1)
4500 NEXT I
4510 PRINT "H=";H,"L=";L
4520 REM************************************************************************
4530 REM NORMALIZE ARRAY
4540 REM************************************************************************
4550 IF E2<>"BS" THEN 4620
4560 FOR R=1 TO Y
4570 FOR C=1 TO X
4580 LET A(R,C)=A(R,C)-L
4590 NEXT C
4600 NEXT R
4610 GOTO 4680
4620 FOR R=1 TO Y
4630 FOR C=1 TO X
4640 LET A(R,C)=A(R,C)-H
4650 NEXT C
4660 NEXT R
4670 REM************************************************************************
4680 REM ADD WORKING ARRAY A TO CUMMULATIVE ARRAY A1
4690 REM************************************************************************
4700 FOR R=1 TO Y
4710 FOR C=1 TO X
4720 LET A1(R,C)=A1(R,C)+A(R,C)
4730 NEXT C
4740 NEXT R
4750 RETURN
4760 REM-----------------------------------------------
4770 REM SUBROUTINE FOR DIAGONAL PASSES
4780 REM-----------------------------------------------
4790 REM INITIALIZE WORKING ARRAYS TO ZERO
4800 FOR R=1 TO Y
4810 FOR C=1 TO X
4820 LET A(R,C)=0
4830 LET B(R,C)=0
4840 NEXT C
4850 NEXT R
4860 REM******************************************************************************
4870 REM HEAT LOWER LEFT TO UPPER RIGHT OR UPPER LEFT TO LOWER RIGHT R
4880 REM******************************************************************************
4890 CLS
4900 PRINT "DO YOU WANT TO HEAT LOWER LEFT TO UPPER RIGHT DIAGONAL? (LLUR/ULLR),"
4910 PRINT "OR UPPER LEFT TO LOWER RIGHT DIAGONALS? (TS/BS);"
4920 INPUT E$ 
4930 IF E$="LLUR" THEN 5560
4940 REM******************************************************************************
4950 REM UPPER LEFT TO LOWER RIGHT, TOPSIDE OR BACK SIDE HEATING
4960 REM******************************************************************************
4970 PRINT "DO YOU WANT TO HEAT THE TOPSIDE OR BACKSIDE? (TS/BS);"
4980 INPUT E1$
4990 IF E1$="BS" THEN 5020
5000 LET Z=1
5010 GOTO 5040
5020 LET Z=-1
5030 REM******************************************************************************
5040 REM UPPER LEFT TO LOWER RIGHT CALC
5050 REM******************************************************************************
5060 FOR P=Y-1 TO 2 STEP -2
5070 LET D=1
5080 FOR I=P-1 TO 1 STEP -1
5090 LET C=1
5100 FOR R=1 TO Y
5110 LET A(R,C)=A(R,C)+0.0065*D*Z*(1/TT)
5120 LET C=C+1
5130 NEXT R
5140 LET D=D+1
5150 NEXT 1
5160 FOR J=2 TO X
5170 LET R=1
5180 FOR C=J TO X
5190 LET A(R,C)=A(R,C)+0.0065*D*Z*(1/TT)
5200 LET R=R+1
5210 NEXT C
5220 LET D=D+1
5230 NEXT J
5240 NEXT P
5250 REM******************************************************************************
5260 REM REVERSE UPPER LEFT TO LOWER RIGHT MATRIX
5270 REM******************************************************************************
5280 LET D=X
5290 FOR P=Y TO 1 STEP -1
5300 LET S=D
5310 LET Q=1
5320 LET C=1
5330 FOR R=P TO Y
5340 LET B(R,C)=A(Q,S)
5350 LET C=C+1
5360 LET S=S+1
5370 LET Q=Q+1
5380 NEXT R
5390 LET D=D-1
5400 NEXT P
5410 LET $=1
5420 FOR P=1 TO X
5430 LET S=1
5440 LET Q=D
5450 LET R=1
5460 FOR C=P TO X
5470 LET B(R,C)=A(Q,S)
5480 LET R=R+1
5490 LET Q=Q+1
5500 LET S=S+1
5510 NEXT C
5520 LET D=D+1
5530 NEXT P
5540 GOTO 6190
5550 REM******************************************************************************
5560 REM LOWER LEFT TO UPPER RIGHT, TOPSIDE OR BACK SIDE HEATING
5570 REM******************************************************************************
5580 CLS
5590 PRINT "DO YOU WANT TO HEAT THE TOP SIDE OR THE BACK SIDE? (Y/N)"
5600 INPUT E1$  
5610 IF E1$="Y" THEN 5640
5620 LET Z=1
5630 GOTO 5640
5640 LET Z=-1
5650 REM******************************************************************************
5660 REM LOWER LEFT TO UPPER RIGHT CALC
5670 REM******************************************************************************
5680 FOR P=2 TO Y-1 STEP 2
5690 LET D=1
5700 FOR I=P+1 TO Y
5710 LET C=1
5720 FOR R=I TO 1 STEP -1
5730 LET A(R,C)=A(R,C)+.0065*D*Z*(1/T)
5740 LET C=C+1
5750 NEXT R
5760 LET D=0+1
5770 NEXT 1
5780 LET E=2
5790 FOR J=2 TO X
5800 C=J
5810 FOR R=Y TO E STEP -1
5820 LET A(R,C)=A(R,C)+.0065*D*Z*(1/TT)
5830 LET C=C+1
5840 NEXT R
5850 LET D=D+1
5860 LET E=E+1
5870 NEXT J
5880 NEXT P
5890 **
5900 REM REVERSE LOWER LEFT TO UPPER RIGHT MATRIX
5910 **
5920 LET D=X
5930 FOR P=1 TO Y
5940 LET S=D
5950 LET Q=Y
5960 LET C=1
5970 FOR R=P TO 1 STEP -1
5980 LET B(R,C)=A(Q,S)
5990 LET C=C+1
6000 LET S=S+1
6010 LET Q=Q-1
6020 NEXT R
6030 LET D=D-1
6040 NEXT P
6050 LET D=Y
6060 FOR P=1 TO X
6070 LET S=1
6080 LET Q=D
6090 LET R=Y
6100 FOR C=P TO X
6110 LET B(R,C)=A(Q,S)
6120 LET R=R-1
6130 LET S=S+1
6140 LET Q=Q-1
6150 NEXT C
6160 LET D=D-1
6170 NEXT P
6180 **
6190 REM ADD ARRAY A TO ARRAY B
6200 **
6210 FOR R=1 TO Y
6220 FOR C=1 TO X
6230 LET A(R,C)=A(R,C)+B(R,C)
6240 NEXT C
6250 NEXT R
6260 REM******************************************************************************
6270 REM FIND LOWEST/HIGHEST VALUE IN ARRAY
6280 REM******************************************************************************
6290 LET H=A(1,1)
6300 LET L=A(1,1)
6310 FOR I=2 TO Y
6320 FOR J=2 TO X
6330 IF L<A(I,J) THEN 6350
6340 LET L=A(I,J)
6350 IF H>A(I,J) THEN 6370
6360 LET H=A(I,J)
6370 NEXT J
6380 NEXT I
6390 PRINT "H=";H,"L=";L
6400 REM******************************************************************************
6410 REM NORMALIZE ARRAY
6420 REM******************************************************************************
6430 IF E1$="BS" THEN 6500
6440 FOR R=1 TO Y
6450 FOR C=1 TO X
6460 LET A(R,C)=A(R,C)-L
6470 NEXT C
6480 NEXT R
6490 GOTO 6560
6500 FOR R=1 TO Y
6510 FOR C=1 TO X
6520 LET A(R,C)=A(R,C)-H
6530 NEXT C
6540 NEXT R
6550 REM******************************************************************************
6560 REM ADD WORKING ARRAY A TO CUMMULATIVE ARRAY A1
6570 REM******************************************************************************
6580 FOR R=1 TO Y
6590 FOR C=1 TO X
6600 LET A1(R,C)=A1(R,C)+A(R,C)
6610 NEXT C
6620 NEXT R
6630 RETURN
6640 END