THEORETICAL AND EXPERIMENTAL STUDIES OF HEAT STRAIGHTENING AND CAMBERING

By

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CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Heat straightening, which is also called flame straightening or contraction straightening, involves controlled application of heat from a gas torch to a specific area of a steel plate. The size, shape, and location of the heated area are carefully controlled(3). Heat straightening has been studied by a number of investigators (1, 3, 5, 6, 7, 8, 10, 12, etc.) since Joseph Holt (4) first applied his knowledge of the effects of thermal expansion and contraction to the straightening of steel members. Heat straightening is economical since the capital investment in equipment is low. Straightening rather than replacing structural membersminimizes material cost. Continual use of the facilities while the members are being heat straightened is possible if proper steps are taken to insure structure stability during straightening. This method is easy to apply once the necessary skills are mastered.

The physical phenomena of the method, such as procedures and heating patterns to be followed, has been studied extensively. However, the use of heat straightening is not widespread because very little experimental information concerning the effects of this method on steel properties is available, even if certain recommended maximum temperatures and exposure times are observed. Moberg (6) called for more research to better define the metallurgical limitations to the use of these methods. Also, very little is known about the residual stress state of heat straightened steels and the possible effects of these stresses in a load-bearing structure.

1.2 Objectives

There are many different mechanical properties that are relevant to a particular engineering material. This thesis is primarily concerned with the study of the microstructure, toughness and residual stress state of heat straightened or cambered mild steels. In essence, the project aims toward the following objectives:

1. To acquire the art of heat straightening as much as possible in order to further the accomplishment of the other objectives.

2. To briefly verify some results of previous theoretical and experimental studies.

3. To study the effects of the types of restraint, the extents of the apex angle of the vee-heat, and the effects of temperature ranges on the rate of straightening or cambering.

4. To study parameters of the straightening and cambering process that most likely influence the

metallurgical and mechanical properties of the steels by:

i. Studying the microstructural changes in steels caused by the straightening or cambering process.

ii. Studying the residual stress state of heat straightened or cambered specimens.

1.3 Scope of Study

To accomplish the above listed objectives, a brief review of steel phases, cold work and recrystallization, and thermal expansion and contraction is included. A detailed summary of previous investigations on heat straightening and its effects on material properties was compiled to illustrate the current state of the art.

The experimental program involves laboratory heat straightening or cambering of thirteen 1/2" x 6" x 24" steel plates. The heat straightening experiment is limited to specimens which are bent to approximately one-half inch offset at the center. The heat cambering experiment is likewise limited to achieving about one-half inch offset at the center of the plates.

The skills of heat straightening include handling of the torch, predicting or observing the plate temperature either with visual temperature measurement or use of temperature paint. These skills were first learned and mastered by heat straightening two of the specimens at melting temperature.

Throughout this study, applicable experimental and theoretical results of previous investigators are followed in setting up the testing procedures. Particular modifications in testing procedures that were necessary and obvious deviations from results reported by other investigators are discussed so as to further improve our understanding of the art of heat straightening.

The study of influences of various types of restraint or external force, the extent of the apex angle of the vee-heat, and the temperature ranges on straightening or cambering are aided by allocating the specimens to various groups as will be explained in detail in Chapter III. The techniques used in investigating possible material degradation caused by heat-straightening include microstructure examination, hardness testing and charpy impact testing.

CHAPTER II

REVIEW OF LITERATURE

2.1 Phases of Steel

The internal structure of materials such as steel involve atoms and the way atoms are associated with their neighbors in crystals, molecules, and microstructures (11). With good understanding of the structure of steel at the microscopic level, the correlation of the structure to properties as well as to applications can be made. In short, a good understanding of microscopic structure leads to better material design, selection and utilization. Any introductory materials science text such as reference 11 will provide a detailed review of steel microstructures.

Steel is an alloy of iron and carbon. At room temperature, the soft and ductile form of pure iron is called ferrite. It has a body-centered cubic structure which does not permit high solubility of carbon atoms. This is due to the fact that the carbon atom is too small for substitutional solid solution, yet too large for interstitial solid solution. The solubility of carbon in this phase is generally less than 0.1 percent.

At temperatures between 912 ^{o}C (1673 ^{o}F) and 1394 ^{o}C (2541^{o}F), pure iron forms a faced-centered structure called austenite. Most of the steel forging and rolling operations are performed at this temperature range since austenite is soft and more ductile. Even though the inter-atomic spacings in austenite are larger than in ferrite, they are still smaller than the diameter of the carbon atom. As a result, the solubility of carbon is limited to about 6 percent at 912 ^{0}C in the two-phase austenite plus carbide region. However, the maximum solubility of carbon in the single-phase austenite region is only 2.11 percent. The phase diagram in Figure 1 illustrates the solubility of carbon in diffrent phases of steel such as the ferrite and austenite phases. By definition, a steel contains less than 1.2 percent carbon; thus the carbon in steel may be completely dissolved in austenite at high temperatures.

Prior to processing a steel, it is heated above the austenite region then cooled at a particular rate. The rate at which the austenite decomposes determines whether the structure becomes fine or coarse ferrite and pearlite, bainite, martensite, or mixtures. Annealing or very slow cooling would give a coarse pearlite in which the carbide particles may spheroidise. This yields the softest steel structure with maximum ductility and minimum strength. Normalizing or air cooling would instead give a finer pearlite and thus a stronger product. Quicker cooling would produce bainite or martensite depending on the composition of steel and previous heat treatment. Martensite is a supersaturated solid solution with a very distorted lattice and a very high dislocation density. It forms the hardest

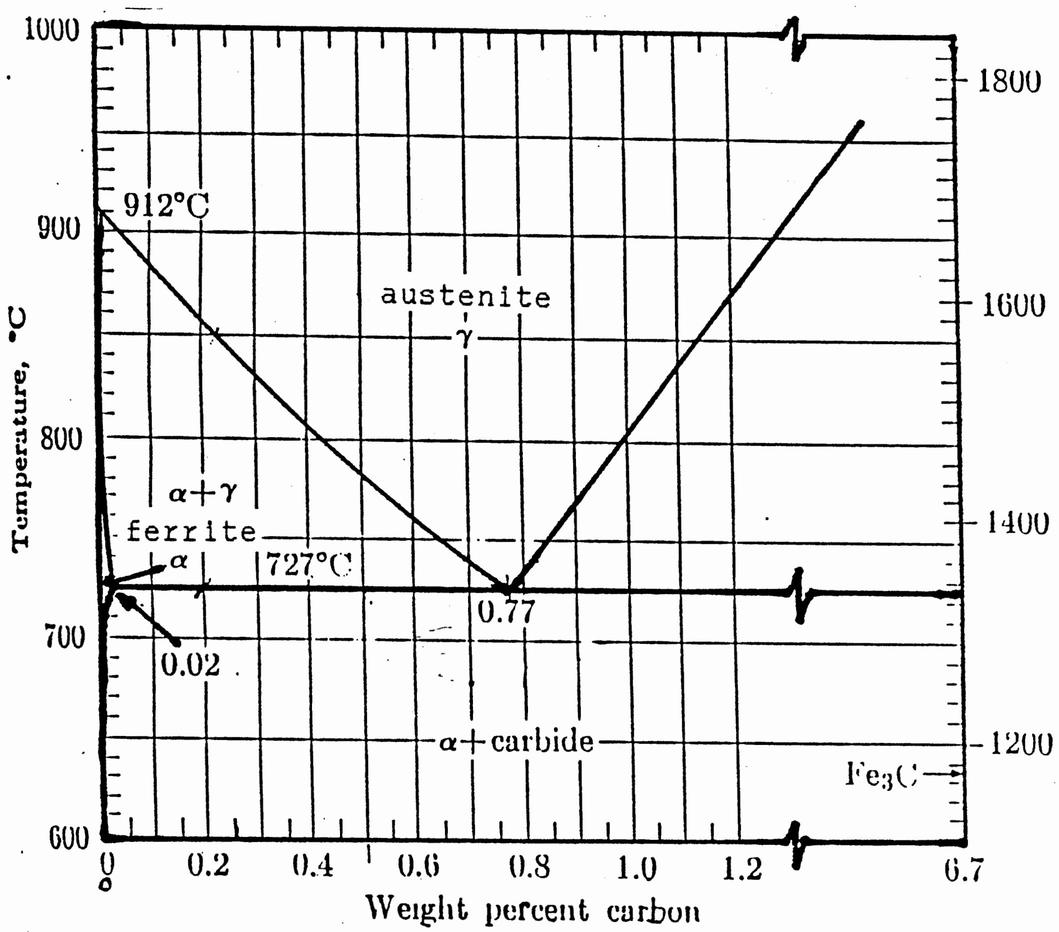


Figure 1: Solubility of Carbon Atom in Ferrite and Austenite Phases of Steel

and most brittle steel. Bainite which contains a dispersion of iron-carbide in ferrite may be obtained by allowing the microstructure of martensite to undergo low-temperature isothermal transformation. Thus, the properties of bainite can be approximated as those of a tempered martensite.

2.2 Mechanical Bending and Recrystallization

Since this research concerns the effects of heat straightening or cambering on mechanical properties of steels, a review of mechanical bending and recrystallization is necessary to facilitate comparisons as well as discussions of the observations obtained from the mechanical bending and actual heat straightening processes.

A bending action at a specific location of a material can be visualized as two groups of uniaxial forces that act in opposite directions (11). Any lengthening or shortening in one direction produces adjustment in the other directions because of the Poisson's effect. The resulting compressive or tensile stresses due to the axial forces eventually resolve into shear stresses corresponding to the slip system of the material. When the critical shear stress is reached, one plane of atoms slide over the next adjacent plane. The ductility of the material determines the extent of plastic deformation, or energy absorption prior to fracture. The moduli of elasticity is not isotropic; thus, at a particular strain, some individual crystals will undergo plastic deformations in its internal structure. However, adjacent crystals which are more favorably oriented may deform only elastically. The resulting differences in volume will create some residual stresses in the individual crystals of the highly stressed material.

Cold plastic bending has a significant influence on the mechanical properties of steel. In this process, all of the plastic formings take place at below recrystallization temperature. Heat is not applied to "soften" the steel in the area to be bent, with the result that a large mechanical load is required. The entanglement of dislocations caused by previous cold work retards subsequent movements of other dislocations resulting in an increase in the critical shear stress (11). Thus, plastically deformed materials exhibit an increase in tensile strength, yield strength, and hardness. However, an increase in work or strain hardening also reduces ductility of the material since part of the ductility was lost in the previous cold-working. Loss of ductility is generally accompanied by decrease in malleability and toughness (3). It may also cause the steel to be more susceptical to fracture and fatigue (9).

In annealing, sufficiently high temperature is supplied to permit greater vibrations of the lattice, thus, allowing the atoms of the deformed crystals to move to form a more perfect, unstrained array (11). Furthermore, the elongated, strained grains produced by cold-working will be replaced by smaller, well-formed grains. By removing strain hardened grains, a work-hardened metal will begin to soften and weaken rapidly; ductility will also be regained. The annealing process also aids in removing the internal stresses, changing electrical and magnetic properties, and removing gases in cold-worked metal. Most crystalline materials are recrystallized during the annealing process.

Recrystallization refers to growing new, more perfect grains from previously deformed crystals without inducing any changes in the atomic compositions or crystal structures. However, local atom rearrangements do occur. The lowest temperature at which recrystallization occurs rapidly is called the recrystallization temperature. This temperature normally ranges from $0.3T_m$ to $0.6T_m$, where T_m is the absolute melting temperature in Kelvin (K). However, sufficient time is always required to permit total recrystallization under the appropriate temperature. With increases in the time of heating, the required recrystallization temperature generally decreases as shown in Figure 2. A material which has a larger amount of strain hardening requires lower annealing temperature since it has more stored energy in the form of vacancies and dislocations than the one with little cold work. Also, highly pure materials anneal more rapidly than alloys because no atom diffusions are hindered by alloying atoms which have different sizes and shapes.

2.3 Thermal Expansion and Contraction

From basic science, it is known that a freely supported material expands upon heating and contracts upon cooling. The change in size is dependent on the material, the

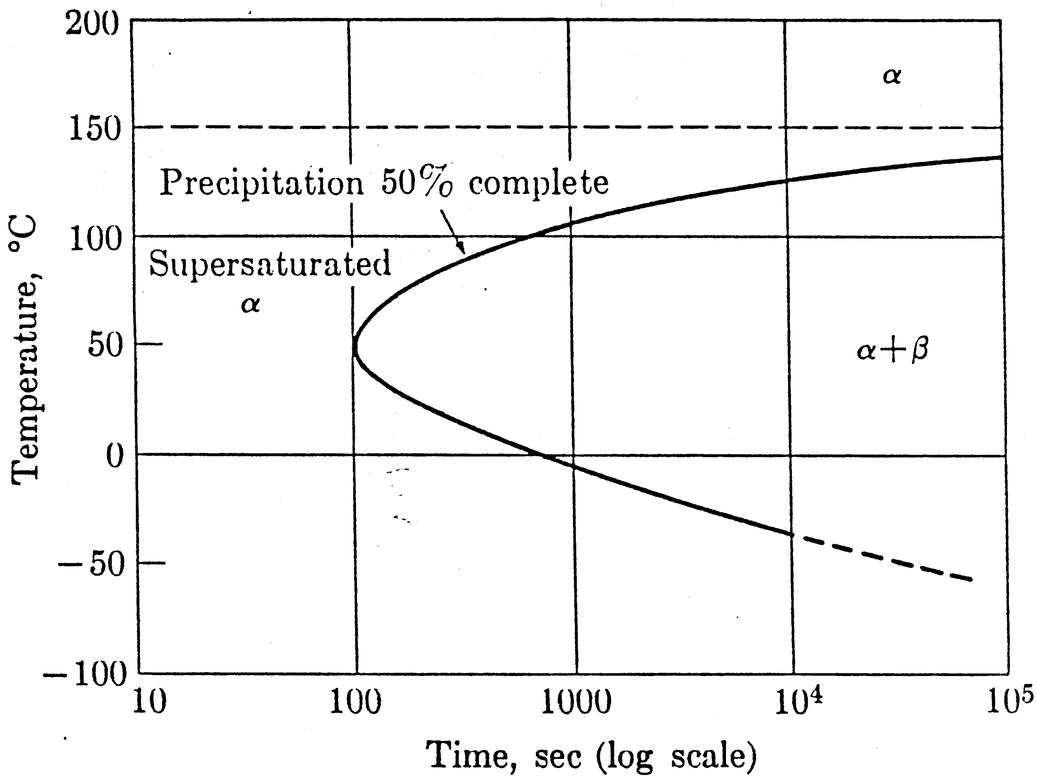


Figure 2: General Isothermal Precipitation Curve

corresponding dimension, and the change in temperature. The increase or decrease in size is proportional to the latter two quantities.

The expansion of a solid material at any increase of temperature is the result of more intense thermal vibrations of the atoms. Generally, the rate of thermal expansion increases slightly with temperature. Hence, the length of a solid material at any temperature may be represented by the following empirical equations as derived by For Chin (2):

For a large temperature range,

$$L_t = L_o (1 + at + bt^2 + ...)$$

where L_t = length at a temperature t^o

L_o = length at a reference temperature

and 'a', 'b', ... are constants, usually positive.

For a small temperature range, constants other than 'a' are assigned values of zero.

The above empirical equation is no longer valid at the temperature range of phase transformation. At this point, changes in the atomic arrangements within the material cause the thermal expansion to be irregular. Above the temperature range of phase transformation, the dependency of thermal expansion on temperature is almost linear again except at a higher rate. This is due to the fact that thermal expansion of austenite is greater than that of ferrite.

The forces that are created during the thermal expansion and contraction processes extend and produce thermal stresses in all directions. Thermal stresses are created in statically indeterminate structures whenever there is a temperature change. Such stresses may also occur when a member is heated in a nonuniform manner irrespective of whether the structure is determinate or indeterminate.

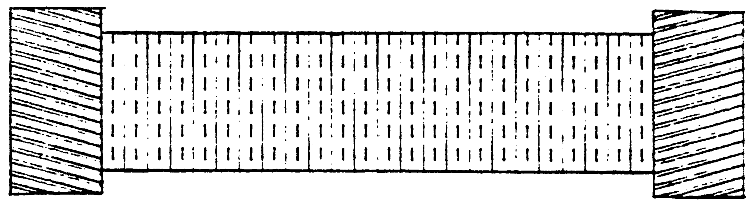
An unrestrained steel that expands thermally in all directions will eventually regain its original size upon cooling. As pointed out by Harrison (3), when certain degrees of restraint are properly imposed in a particular direction, it retards thermal expansion in that direction but aids expansion in perpendicular directions. However, restrained expansion in a particular direction does not interfere with subsequent contraction along the same direction. Thus, upon cooling, the restrained direction will be shorter in length. The amount of contraction also depends on prior plastic deformation due to heat application. The above phenomenon, which is the basis of heat straightening or cambering, is illustrated in Figure 3.

2.4 Heat Straightening

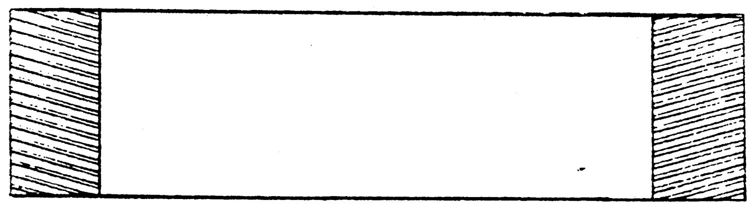
2.4.1 Techniques

A bent member may be straightened by shortening the longer edge, lengthening the shorter edge, or a combination of both (3). The phenomena occurring in restrained thermal expansion and contraction has been used in heat straightening in the following ways:

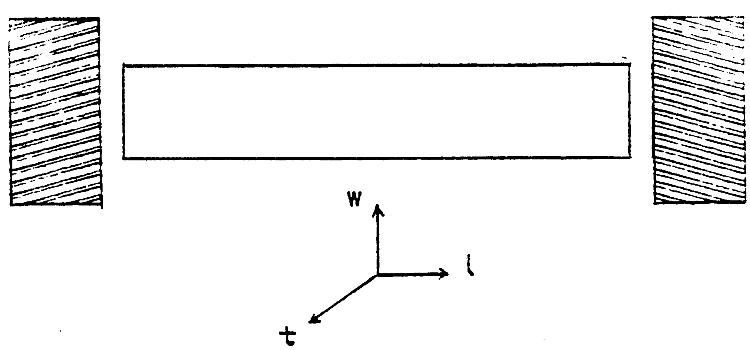
1. Expansion is restrained in the longer edge of a bent structural member being heated. The yielding material



a) Heated Region



b) Thermal Expansion (in t and w directions) while heated



c) Contraction in all directions after Cooling

Figure 3: Restrained Thermal Expansion

will expand into itself, and thus achieve net expansion in the perpendicular directions.

2. Then, the restrained edge that was kept at constant length will contract and straighten the member upon cooling. The same phenomena occurs in heat cambering.

According to Holt (4), in order to make this method work, portions of the member must be cold enough, strong enough, and so situated as to force the metal to yield unless some outside forces can be added. Figure 4 shows a scaled drawing of a flat bar about one quarter of an inch thick, two inches wide, and approximately two feet in length which was used by Holt to explain the process of heat straightening. The metal at A and B is cold and rigid when heat is rapidly applied at C, forcing it to expand. As a result, the metal at C is placed in compression. As the heat moves toward B, the heated section is widened.

As the flame moves from point C, the metal at that point contracts with a decrease in temperature, and becomes more rigid. Thus, it assists in restraining the hotter metal at the torch tip. The widening heated area and the contracting metal behind it compress the edge B, which does not restretch but contracts on cooling so that the bar is bent edgewise. The increasing width of the vee-heat results in a residual curvature by allowing nonuniform expansion and thermal yielding of the metal. The point A should not be heated directly with the flame. At most, it should only be exposed to the temperature created by the conductivity of the metal. The metal at point A restrains expansion in the

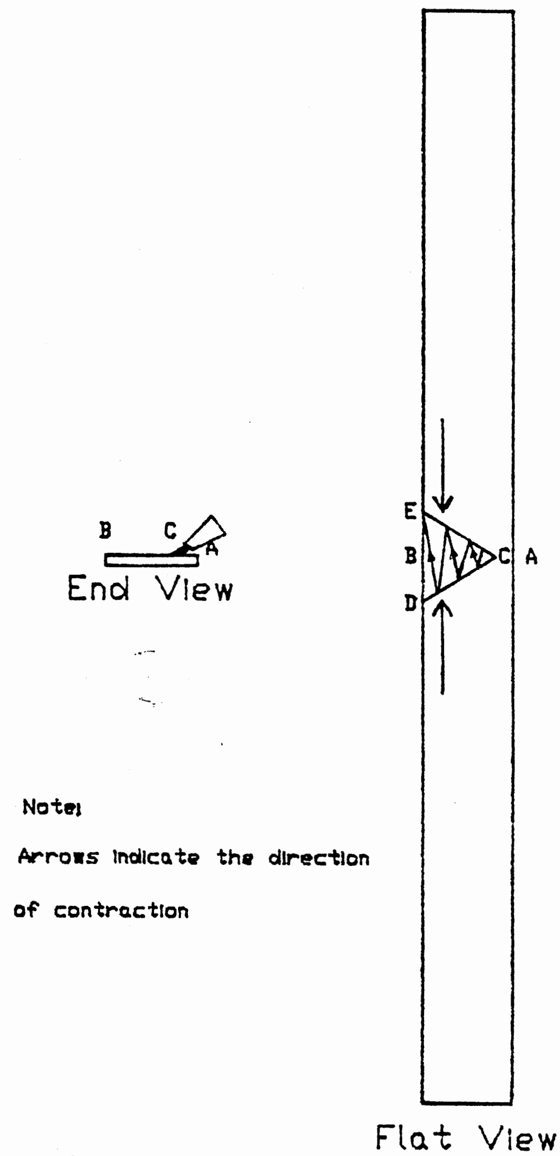


Figure 4: Holt's Illustrative Heating Pattern

vee-shape heated area, and will perform this function most effectively if it remains as cool as possible.

In Figure 5, a piece of rectangular lamellar wood is subjected to a constant-temperature heat source which is turned on and off occasionally. While being heated, the expansion at the bottom surface is restrained by the top surface which is always cooler. When the heat source is turned off, the bottom surface begins to contract thermally and results in a net curvature as shown.

The degree of straightening or cambering obtained will vary with the number, location, and geometry of the heated areas (5). Other variables include the sequence in which the different areas are heated, the rate of heating, the heating temperature and the use of auxiliary mechanical force.

The straightening action relies on the constraint supplied by the cold metal that surrounds the heated zone (5). The maximum constraint is obtained when the thermal gradient is steepest either within the heated zone itself or between the heated zone and surrounding cold metal. Upon completion of a particular heating, the continuous thermal gradient must always be extending from the base to the apex side of the vee-heat. Rapid application of heat into localized areas of steels can minimize the amount of heat that is conducted into the surrounding cold material and results in more straightening per heating-cooling cycle. Also, once an area has been heated, it should not be immediately reheated. The initial heating causes the steel

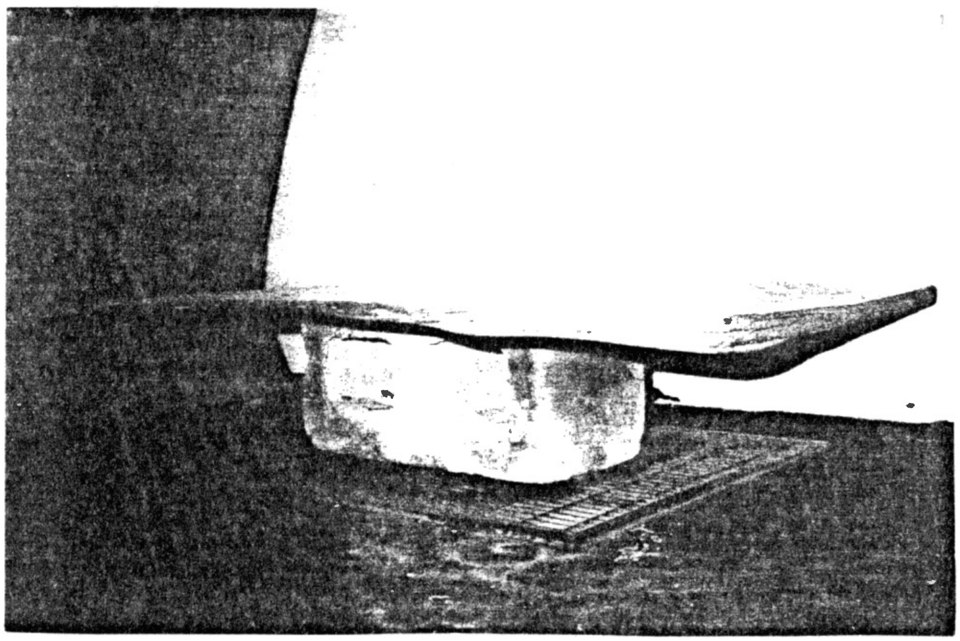


Figure 5: A Heat-Cambered Lamellar Wood

to expand. As the steel that was subjected to initial heatings begins to cool down and contract, it produces longitudinal residual tensile stress in this area, thus, exerting a contraction force that is equivalent to the yield point at that particular temperature (12). This force provides additional confinement required to upset the lower portion of the vee-heat that is being heated. Instantaneous reheating causes thermal expansion to occur in the direction of these tensile stresses rather than in the plate thickness causing little or no additional straightening action.

Sometimes, the application of heat alone will not straighten a member. This is especially true under the following conditions (10):

1. the member does not have sufficient metal in the proper planes to be heated or to cause upsetting of the heated region;

2. large forces from the structure tend to act counter to the straightening processes.

In these cases, an auxiliary mechanical force can be applied to cause compression in the longer edge of the bent member up to the yield point at the heating temperature. When heat is applied, all expansions will be forced to go into compression and considerable savings in time could be obtained.

2.4.2 Temperature Indicating Elements

In practice, some States allow visual temperature measurement in heat straightening or cambering, while others specify use of temperature paint, temperature crayons, or a surface pyrometer. Table I shows some surface colors that are approved for recognizing a particular temperature without using any temperature indicating products (10).

TABLE I

TEMPERATURE AND THE APPROVED INDICATING COLORS

Temperature (oF)	Indicating color
1100	dull red dull cherry red
1100-1200	dark cherry red disappearing red
1200	dull red dull cherry red plantom black light red
1200-1400	cherry red

From the table, it is apparent that the temperature measurement cannot always be predicted or controlled accurately. Even an experienced operator could misjudge the temperature levels by a couple of hundred degrees.

2.5 Effect of Straightening on Mechanical and Metallurgical Properties

Pattee and associates (7) pointed out that considerable questions arise regarding the effects of the straightening parameters on the mechanical and metallurgical properties of metals since there is little control of parameters such as temperature, cooling rate, and use of peening. All of these parameters are capable of inducing changes in microstructure leading to changes in tensile and impact strength, hardness, and energy absorption. By understanding the nature of these changes, the appropriate heat straightening steps may be specified.

2.5.1 Temperature

In the common range of heat straightening or cambering temperatures, which is between 500 ^{o}F and 1400 ^{o}F, a metal being heat-straightened generally exhibits a decrease in strength and an increase in ductility (3). Consequently, less force is required to change the shape of the piece or to produce buckling. However, Weerth (12) found that a heat-cambered metal exhibits opposite observations in strength and ductility after the metal has cooled. He attributed this phenomenon to the combined effects of strain aging and strain hardening.

Previous studies indicate that steels are expected to experience no serious property degradations after cooling as long as heating temperatures are limited to 1200 ^{o}F. The maximum heating temperature permitted in various states within the United States ranges from 1100-1200 ^{o}F. Occasionally, lower maximum temperatures of 800 ^{o}F and 1000 ^{o}F are imposed on low-strength bridge steels such as A7 and A36 to prevent sudden failure of the entire structure. These are as-rolled steels with a maximum yield strength of about 35,000 psi (5). Some investigators prohibit heating on the high-strength bridge steels such as A242, A441, A572, and A588. These are as-rolled, normalized, or stress relieved steels with maximum yield strengths of about 50,000 psi. Heat treating of quenched-and-tempered steels, such as A517 Grade B (NAXTRA-100) and A517 Grade F (T-1), is not permitted. Yield strengths of around 100,000 psi are achieved in these steels by heating to approximately 1600 to 1700 ^{o}F, rapidly cooled to form martensite, and then reheating at 1050 to 1275 ^{o}F to temper (7). Thus, heating these steels to an elevated temperature might cause them to lose any benefits of previous heat treatments by undergoing the annealing or recrystallization process.

2.5.2 Cooling Rate

Frequently, the heated area is allowed to cool at a rate determined by the radiation characteristics of the metal, by convection due to air currents, and by transfer of heat into cooler areas of plate or structure. However, use of a water spray or air blast could increase the cooling rate substantially.

Nonuniform cooling could produce an uncontrolled shrinkage pattern resulting in added distortion. On the other hand, accelerated cooling may produce hard spots at a location in the heated area that experienced temperature excursions above the austenite transformation temperature, even if it is applied uniformly. These areas would be in an as-quenched condition, which would exhibit higher strength and lower notch ductility. Repeated heat applications could result in microcracking and subsequent reduction in fatigue life of the metal. In practice, cooling with dry compressed air is permitted after the steel has cooled to 600^{o} F (5).

Besides temperature, cooling rate also could affect the transformation characteristics of heated-treated steels, thus, causing some changes in the microstructures (7). Different cooling rate could be obtained by methods such as water-spray, air-blast, or convection.

2.5.3 Peening

Occasionally, force is applied to cause tension in the shorter edge and compression in the longer edge of a bent structural member while it is being heat-straightened (3). Release of the tensile stresses which oppose the straightening process can be achieved by either yielding the tensioned region or by applying light peening which lengthens the steels. However, the applied external force may induce some residual stresses in the member and use of heavy or violent peening can cause the structural member to work harden. All these defects can be reduced by heating the stressed or hardened area at completion of heat straightening.

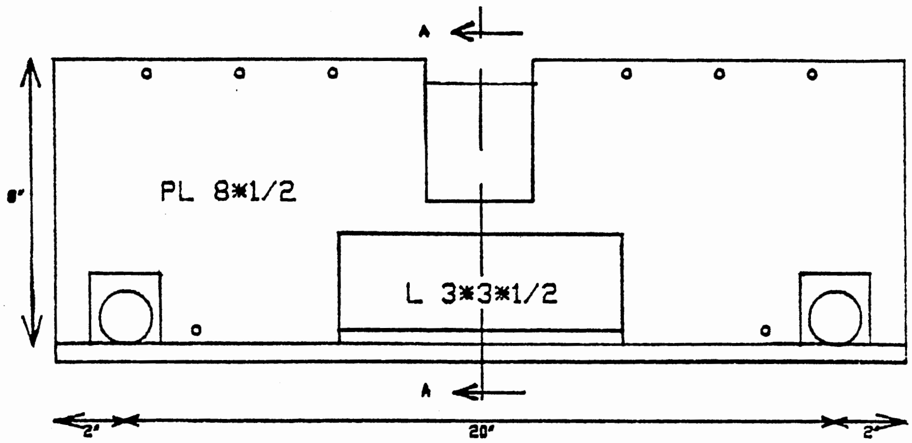
CHAPTER III

METHOD AND PROCEDURES

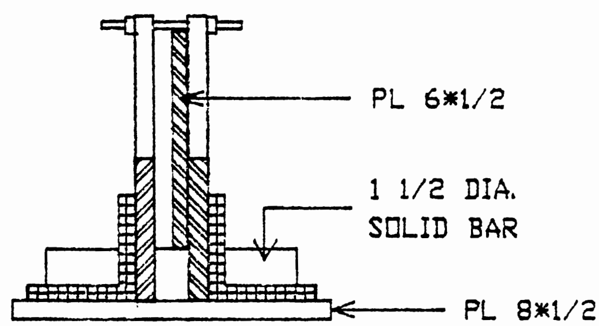
3.1 Bending Setup

A bending jig was constructed to prevent lateral buckling of the plates while they were mechanically bent. The setup of the bending jig in the compression machine is as shown in Figure 6. One of the two vertical plates was welded to the base plate. The second vertical plate was bolted to the welded plate to permit positioning, tightening or losening of the testing specimen while it is being bent. One of the two dial gages attached was used to measure the vertical movement of the compression arm, hence, vertical offset of the testing plate, while another was used to measure the horizontal movements of both the testing plate and the two restraining plates. The horizontal movement of the bending jig was always limited to 0.015 inch in both lateral directions to prevent excessive bucklings. In fact, it was found that no plastic strains was induced during the entire bending process.

A strain gage was attached to the bottom of one of the bending specimens to measure horizontal normal strain. A portion of the stress-strain curve is shown in Figure 7 to characterize the mechanical properties of the specimens and

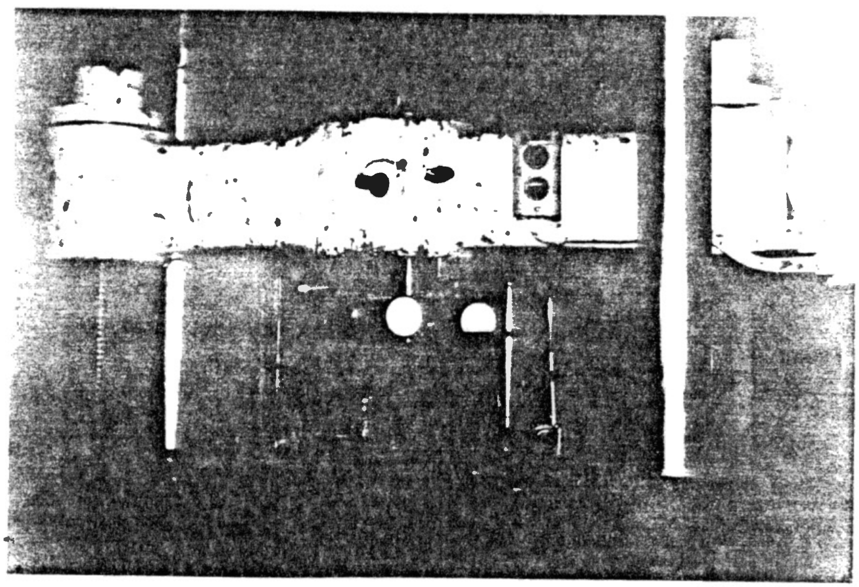


ELEVATION



SECTION A-A

a) Bending Jig



b) Setup in Compression Machine

Figure 6: Bending Jig and its Setup in Compression Machine

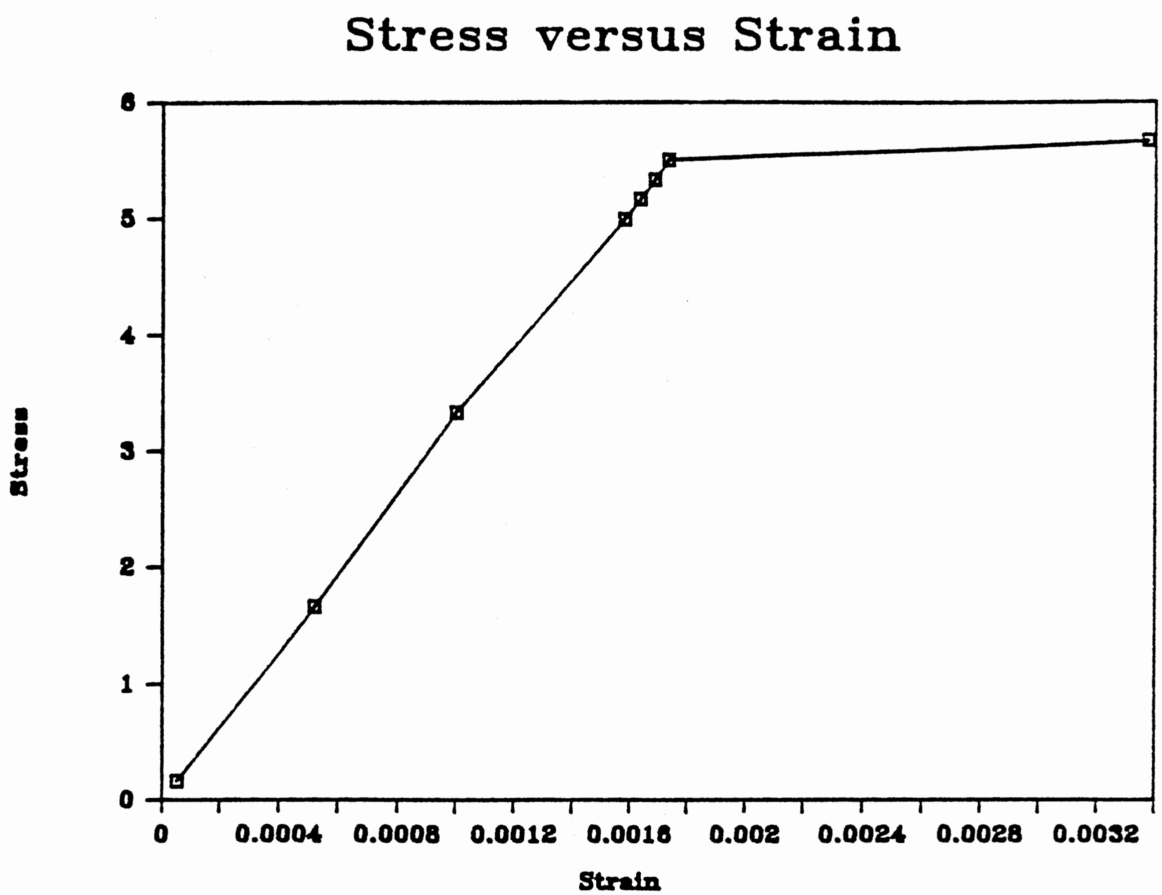


Figure 7: Stress versus Strain Curve of the Mechanically Bent Specimen

to illustrate the extent of the bending effect.

3.2 Heat Application

An oxyacetylene torch was used as the heat source for heat straightening and cambering. Although a high heating rate can be achieved through the use of high gas pressure, the acetylene and oxygen pressures were limited to 5 psi and 25 psi respectively. Acetylene becomes unstable at pressure approaching 30 psi, and the maximum allowable pressure is 15 psi (3). The pressures used in all heatings were the recommended pressures for cutting a one half inch thick plate with a cutting tip. However, a Victor #5 single orifice heating tip was found to be most efficient for a plate thickness of 1/2", vee-heat depth of 4.5", and an apex angle of 67 degrees. A large "rosebud" or multiorifice torch tip was not used since it tends to spread the heat within the small area, and apparently produced small temperature gradients between the heated area and surrounding cold area as well as within the heated area itself. The multiorifice tip also makes heat application less controllable, and tends to cause distortion of the plate. Weerth (12) recommended the use of multi-orifice or "rosebud" heating tips with oxyacetylene, oxy-propane or oxy-natural gas on material over 1/2" in thickness. Even though the thickness of the heating specimens did not necessitate the use of two-side heating, heating was applied at each surface alternately to minimize a lateral buckling perpendicular to the plate surface.

The maximum plate temperature allowed on Specimens Ds, Es, and Gs as tabulated and explaуned in Table III was 1200 ^{o}F even though the surface melting temperature was 2800 ^{o}F . Beyond 1200 ^{o}F, steel shrinkage becomes irregular and mild steel begins to display metallurgical transformations which may adversely affect material performance (2). The instantaneous temperatures during a particular heating were always kept as constant as possible. This temperature was achieved as rapidly as possible without overheating the specimens and was closely controlled with the use of "Temp-Alarm" which is a temperature sensitive, color-changing paint.

"Temp-Alarm" has an original color of red and changes color with temperature as shown in Table II. The heated spot was always kept at yellow to grey color with surrounding rust color as shown in Figure 8.

TABLE II

TEMPERATURES AND CORRESPONDING SIGNAL COLORS OF "TEMP-ALARM"

Temperature (^{o}F)	Transition Color
700	Rust
875	Orange
1000	Yellow
1475	Grey Green

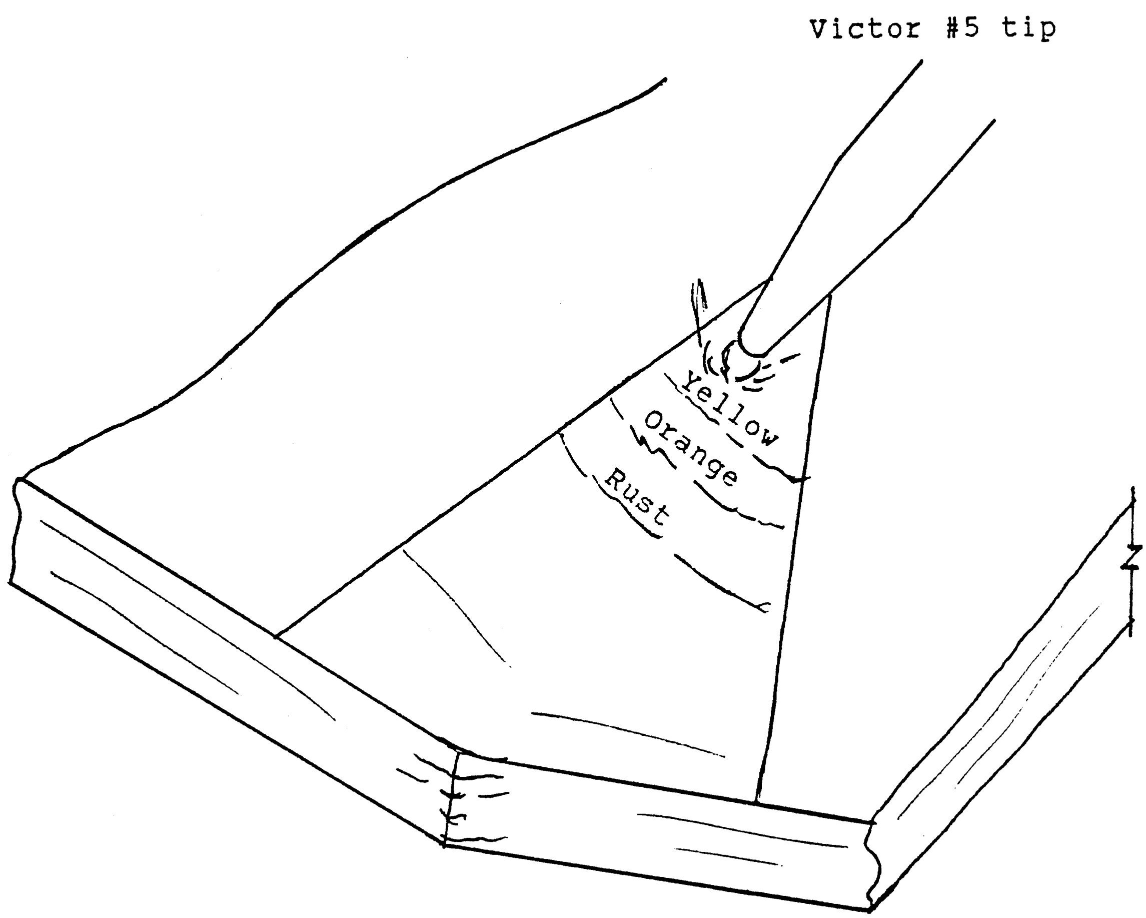


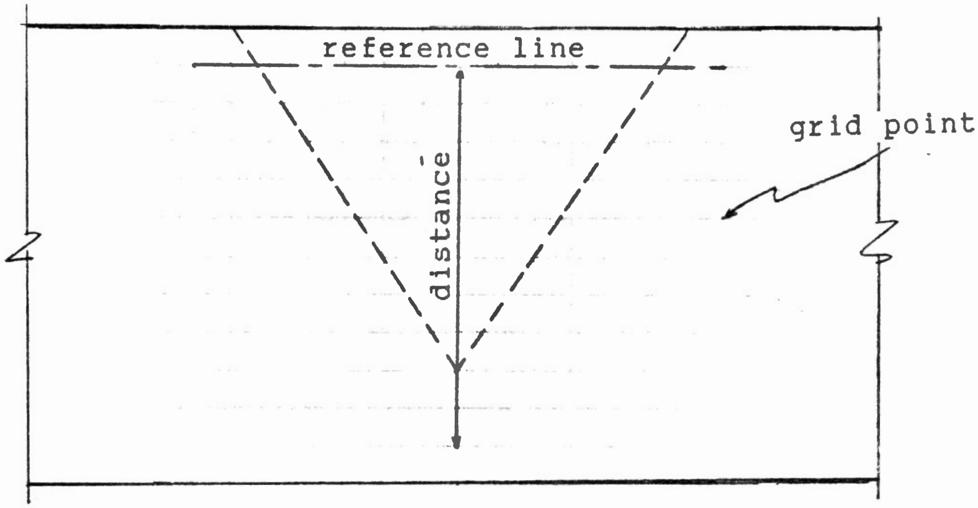
Figure 8: Observed Color Pattern of the "Temp-Alarm"

The deformation response of the heated specimens is also time dependent, thus, cooling was allowed to take place in still air for at least forty five minutes, allowing the specimens to cool to below 600 ^{o}F. This ensured uniform cooling rate as well as full use of the contracting properties of the straightening method.

3.3 Specimen Preparation

All specimens used in this study were hot rolled plates made from ASTM A-36 steel. This is a low carbon, ferrite-pearlite, low strength, weldable structural steel which is most widely used in bridges, buildings and for other general structural purposes. The dimensions of all the plates are 1/2" x 6" x 24". A grid with squares of 1/2" x 1/2" was marked on each plate to facilitate the study of contraction or expansion in the plates. The rate of straightening or cambering is obtained by measuring the distance of the last point from the horizontal line formed by joining the second left-most and second right-most points at the apex-angle side of the plate as shown in Figure 9 a).

The allocation of plates to various phases of the study is shown in Table III. Specimens B, C, D1, D2, D3, E1, E2, F1, and F2 were bent with the bending jig to about half of an inch offset at the center of the plates prior to subsequent testings. Specimen C was then straightened with the same setup. Specimens D1, D2, D3, F1, F2, G1, G2, and G3 were heat straightened or cambered with an apex angle of 67^{o} located at one and a half inches from one edge of the



a) Rate Measurement and Vee-Heat Geometries

b) Typical Vee-Heat

Figure 9: Rate Measurement and Layouts of Vee-Heat Geometries on Flat Plate

TABLE III

ALLOCATION OF TEST PLATES

Plate	Uses
A	Standard Undeformed Specimen
B	Force-bent
C	Force-straightened Specimen
D1	Heat-straightened at 1200oF without outside restraint
D2	Heat-straightened at 1200^{o} F with outside restraint
D3	Heat-straightened at 1200^{o} F with an applied moment
E1	Heat-straightened at 1200^{o} F and full depth without outside restraint
E2	Heat-straightened at 1200^{o} F and full depth with outside restraint
F1	Heat-straightened at melting temperature (without buckling)
F2	Heat-straightened at melting temperature (with buckling)
G1	Heat-cambered at 1200oF
G2	Heat-cambered at 1200^{o} F with outside restraint
G3	Heat-cambered at 1200^{o} F with an applied moment

plates, whereas specimens E1 and E2 were heat straightened with the same apex angle begun at the edges. The two types of vee-heat geometries and layouts on the plate were also shown in Figure 9. All the heatings were placed at the location of maximum distortion. Table IV illustrates matching of various plates with their respective objectives.

TABLE IV

MATCHING OF VARIOUS PLATES AND THEIR RESPECTIVE OBJECTIVES

Group	Plate(s)	Objectives
I	A, B, D1, D3, F1, G1	Comparison of microstructures
II	D1, D2, E1, E2, G1, G2	Study effects of restraint conditions on rate of heat straightening and cambering and compare rate of straightening and cambering
III	C, D1, D3, G1, G2, F2	Study of residual stresses across the heated areas
IV	A, B, C, D1, E2, G1	Study of change in toughness (Charpy Impact Test, Rockwell Hardness Test)

A bar clamp was used to supply restraint by applying some axial force at the apex-angle side of the plate D2 and E2 while heat was being applied. It was then removed to the opposite side while the plate was left to cool in still air. The outside restraint used on specimens D3 and G2 is shown in Figure 10. From the graph of yield strength versus temperature for ASTM-A36 steel in Figure 11, which was derived by Weerth (12), the yield stress at 1200 ^{o}F was found to be 13 Ksi. The corresponding yield strength is thus calculated as follow:

13 Ksi = M*y/I ; y = 3 in.

; I = ((0.5 in)*(6 in)^3)/12

Thus, M = 3.25 ft.Kip

In order to permit heat straightening and cambering under some auxiliary forces without buckling, specimens D3 and G2 were heat-straightened and heat-cambered respectively while they were resisting a bending moment of less than 3.25 ft-Kips at the center of the vee-heats.

3.4 Sectioning

Strain gages were mounted to specimens C, D1, D3, G1 and G2 at three locations along the center lines that bisect the apex-angles. The longitudinal axis of the gages was orientated to be parallel to the longitudinal axis of the plates. Specimens were then sectioned at about two inches width along the central line. The normal strains at each location were taken after the sectioning process. The displacements are the indications of the residual stress state of the particular specimen at the specified locations. The setup of the process was as shown in Figure 12. Figure 13 shows how specimen F2 was cut into several strips to facilitate the study of thermally induced residual stress.

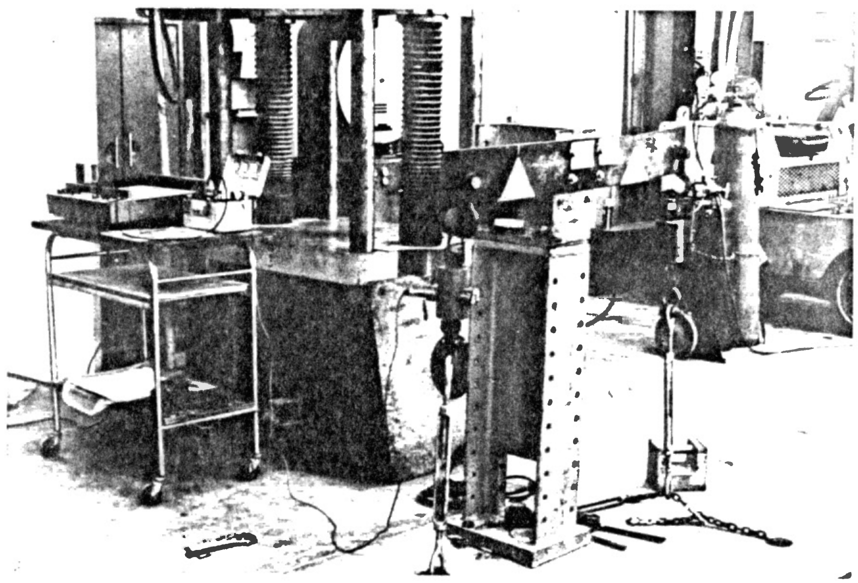


Figure 10: Application of Auxiliary Force in Heat Straightening and Cambering

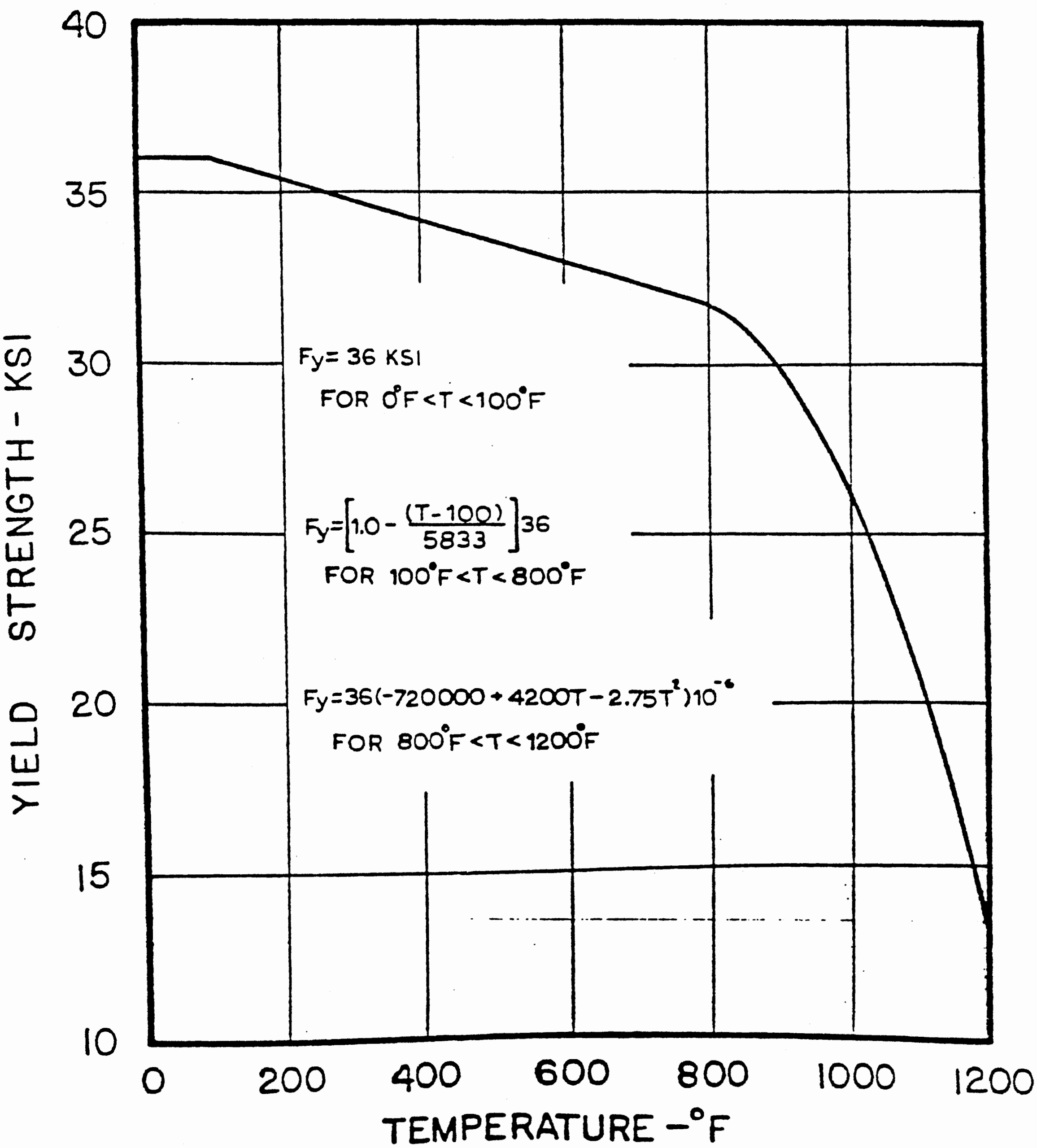


Figure 11: Yield Strength Versus Temperature for ASTM-A36 Steel

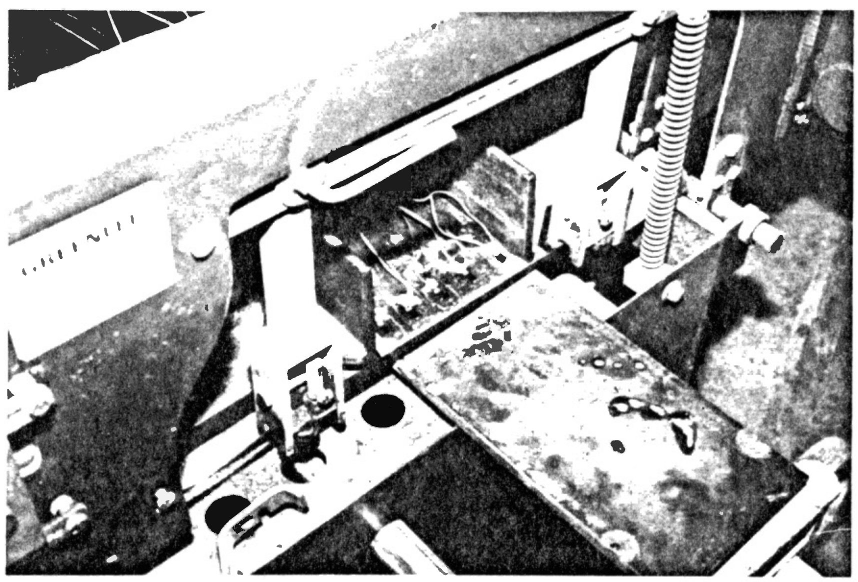


Figure 12: Location of Strain Gages

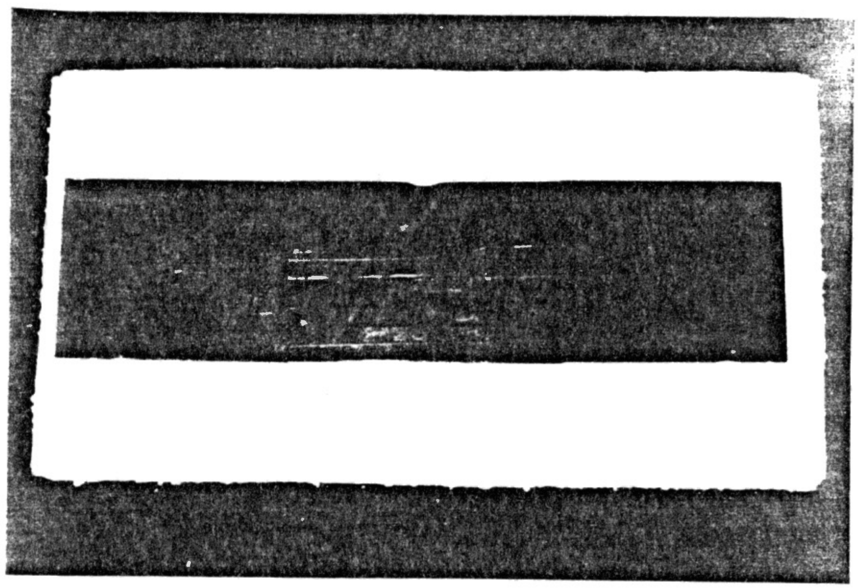


Figure 13: Strip Pattern of Specimen F2

3.5 Microstructure Examination

After the appropriate force straightening, heat straightening or heat cambering operations, a one-inch wide strip was cut out of the center of the following specimens: Specimen A, B, D1, D3, and G1. All of these strips were prepared for microstructural examination by grinding and polishing through 1 Micrometer alumina. The specimens were then etched as necessary in 2% Nital. The microstructures along the longitudinal direction at the base of the vee-heat were examined for possible changes in grain sizes, shapes, boundaries, and phase. Photographs of each specimen were subsequently taken at optimum magnification to be examined.

3.6 Charpy Impact Test

Processes such as annealing occurring during heat straightening could cause small variations in composition or structure within a specimen. These changes would, in turn, affect the variation of metal toughness with temperature. The change in the behavior of heat-straightened materials under the impact of a moving mass should be investigated to ensure overall safety of the restored structure.

In a Charpy impact test, a notched specimen which is supported as simple beam is struck with a falling weight. The dimension of the standard three-point impact loaded Charpy specimen is 10mm x 10mm x 55mm with a 45^{o} notch which is 2mm deep and with 0.25mm root radius. This test determines only the energy required to produce rupture at various temperatures. The fracture energy absorption for a particular specimen can then be plotted against corresponding temperatures. From the curve, the brittle-to-ductile transition temperature for the specimen can be determined. The amount of work required to produce brittle fracture is normally many times smaller than that required to produce plastic fracture. The objective of this investigation is to determine if the transition temperature of the heat-straightened or heat-cambered specimens is lowered relative to that before the processes. The test for metals is described in ASTM E-23.

Several V-notch specimens are made from each of the following plates: A, B, C, D1, E2 and G1 to study the effects of heat straightening on the ductility temperature. Several temperatures should have been taken by immersing the specimens in: a) boiling water at 100 ^{o}C, b) room temperature at 20 ^{o}C, c) ice water at 0 ^{o}C, d) iced-brine at -15 ^{o}C, e) dry ice and alcohol at -80 ^{o}C, and f) liquid nitrogen at -190 ^{o}C. Due to budgetary contraints, only the bottom plateau of the curve (-80 ^{o}C) will be investigated.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Assumptions

The following assumptions are made to simplify analysis and discussion of experimental results.

1. Steel expansions and contractions are identical on both sides of the vertical line bisecting the apex angle of the vee-heat.

2. There is no significant temperature gradient through the plate thickness.

3. Room temperature is constant throughout the experimental study.

4.2 General Observations

Prior to the straightening or cambering effects, the vee-heat regions generally expand and then contract to the original shape as shown in Figure 14. The amount of contraction eventually exceeds prior expansion to produce the desired straightening or cambering.

Figure 15 illustrates the movement of points on a specimen as it is bent, straightened, and sectioned. Points shown in the figures are punch marks placed on the specimen in a rectangular grid pattern prior to any specimen

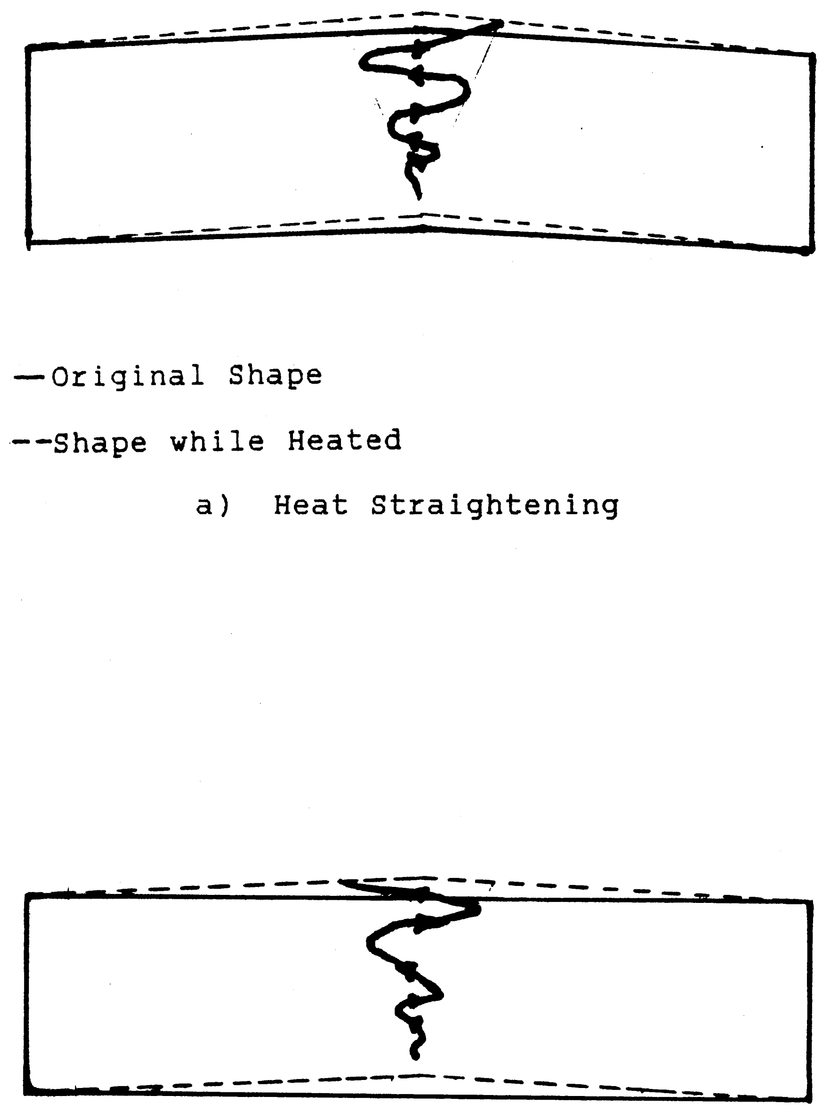
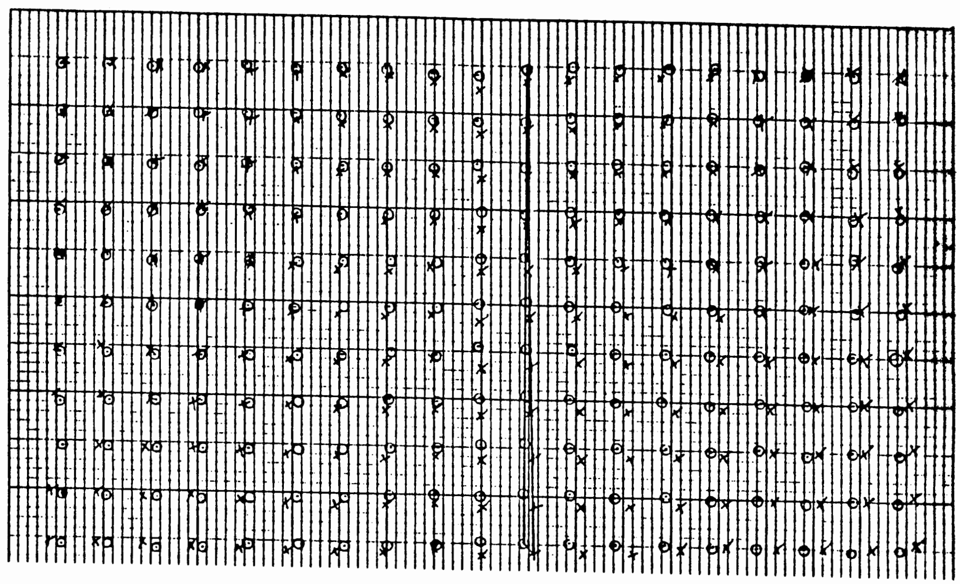


Figure 14: Expansion and Contraction Patterns Prior to the Straightening or Cambering Effect

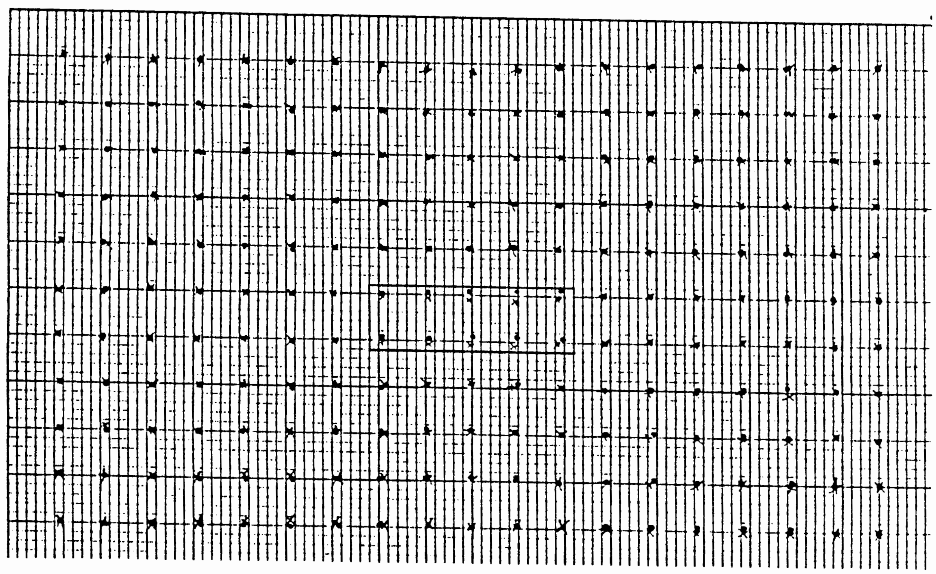


● Heat-Straightened Grid Pattern

✗ Force-Bent Grid Pattern

a) after Heat Straightening Process

Figure 15: Movements of Grid Points on Heat-Straightened Specimens



• Heat-Straightened Grid Pattern

x Grid Pattern after the Residual Stress is Released by Method of Section

b) after Sectioning Process

Figure 15: Movements of Grid Points on Heat-Straightened Specimens

deformation. From Figure 15 a), it can be seen that the marks move uniformly toward the undeformed position. The largest movements occur near the center of the bent specimen especially at the elongated part of the specimen. The amount of horizontal contraction at a particular location was linearly proportional to the length of the corresponding heated strip as shown in the enclosed triangular area. In addition, upsetting of the specimens was especially apparent at the highly constrained areas at the middle of the vee-heats, as evidenced by a thicker cross section after several heatings. The extra volume was obtained from surrounding metals which were subjected to high tensile stresses due to eventual contraction of the heated region. As illustrated in Figure 15 b), the punch marks at the highly compressed central region move from their confined positions after sectioning.

As shown in Table V, specimens D1, D2, F1 and F2 exhibited heat straightening effects after approximately twenty heat applications. On the other hand, specimens G1 and G2 exhibited heat cambering effect almost immediately. Both cambering-specimens also required fewer heatings to achieve an equivalent degree of bend. Heat straightening effects on specimen with applied moment (Specimen D3) and on specimens with full depth heating (Specimens E1 and E2) also occurred instantaneously. Apparently, the applied moment and full-depth heating supplied enough compressive force or provided enough contracting metals to resist the residual stresses which oppose the straightening process. However, the rate of straightening was not affected substantially.

TABLE V

NUMBER OF HEATINGS REQUIRED AND RATE OF STRAIGHTENING OR CAMBERING

Specimen	Number of heat applications required		Rate
	To Initiate	To Complete	(+/- in/heating)
D1	20	44	-0.0046
D2	20	44	-0.0047
E1	1	16	-0.0122
E2	1	32	-0.0069
F1	20	27	-
F2	20	26	-
G1	1	16	+0.0066
G2	1		

Specimens F1 and F2, which were heat-straightened at surface melting temperature, required only six to seven heatings to complete straightening after straightening effects were first initiated. This could be explained by referring to the shrinkage curve developed by For Chin (2) as shown in Figure 16. For SAE 1020 (Refer to Section 4.3.3), no shrinkage was observed below 675 ^{o}F. Shrinkage varies linearly with temperature between 675 ^{o}F and about 1160 ^{o}F. The variation of shrinkage with temperature is irregular between 1160 ^{o}F and about 1540 ^{o}F due to phase transformation. At melting temperature, which is above phase transformation temperature, the amount of shrinkage still varies linearly with temperature but at higher rate. For SAE 1020 hot-rolled steel, the equation derived to predict the amount of shrinkage at a particular temperature below phase transformation temperature is shown below,

$$S = 0.1316*T - 89 \quad \text{for } 675\,^{o}F < T > 1160^{o}$$

where S = shrinkage in 1/10,000 inch per inch,

and T = temperature of specimen in ^{o}F.

From the shrinkage equation or Figure 16, the shrinkage rate at the heating temperature (1200 ^{o}F) is about 0.006892 inch per inch of heated length in the direction being considered. Experimentally, the total shrinkage undergone by specimens D1, which was not subjected to full depth heating, is measured to be 0.250 inch at the 5.3333-inch-long strip after twenty heatings. Based on the shrinkage rate, an unconfined strip of the same length would have a total shrinkage as calculated below,

(0.006892 in/in)*(5.3333 in)*(24 heatings)
= 0.8822 inch.

The percentage difference between the measured total shrinkage (0.250 in.) and calculated total shrinkage (0.8822 in.) is about 72. For specimen E1, which was subjected to full depth heating, the actual shrinkage is 0.375 inch after

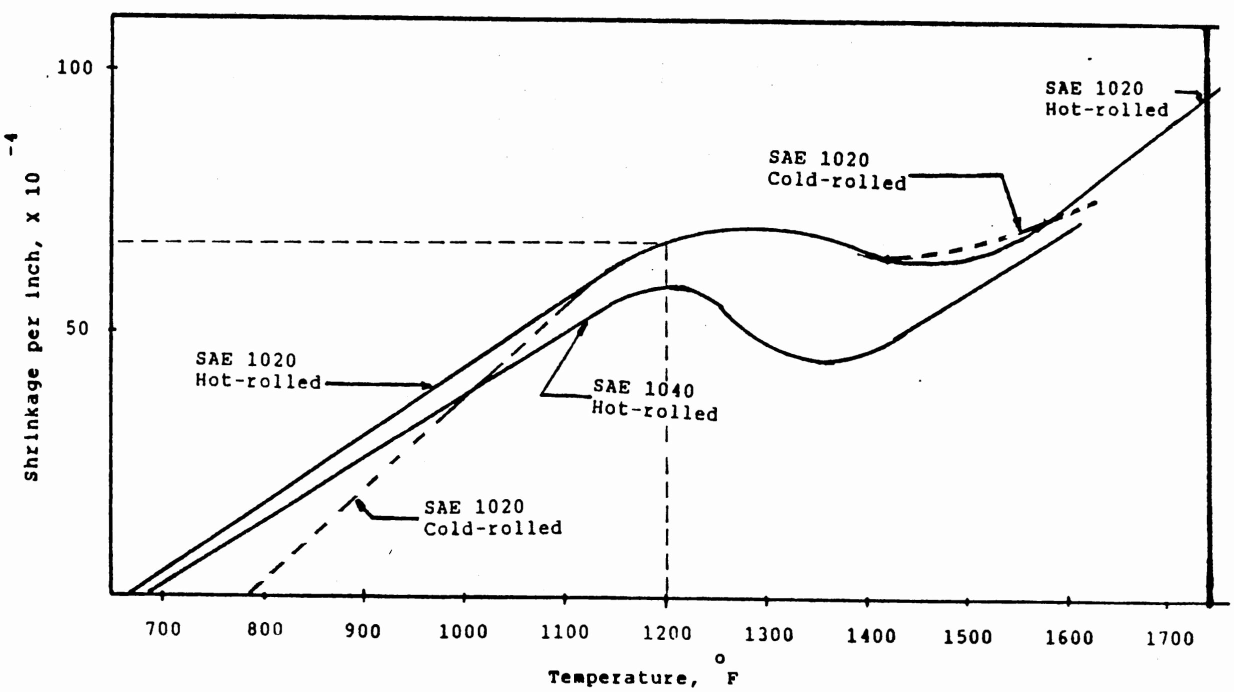


Figure 16: Shrinkage Curve for Various Steels

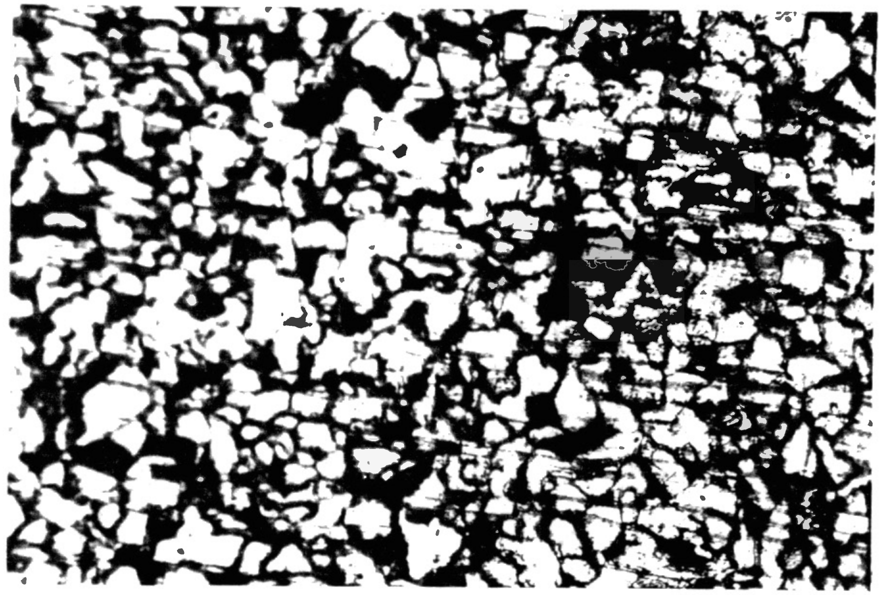
sixteen heatings. However, the predicted shrinkage based on the same number of heatings is 0.5881 inch. The corresponding percentage difference is only 36. These observations clearly show that the rate of straightening due to full depth heating can be more closely predicted by the specimen's shrinkage behavior.

4.3 Specific Comparisons

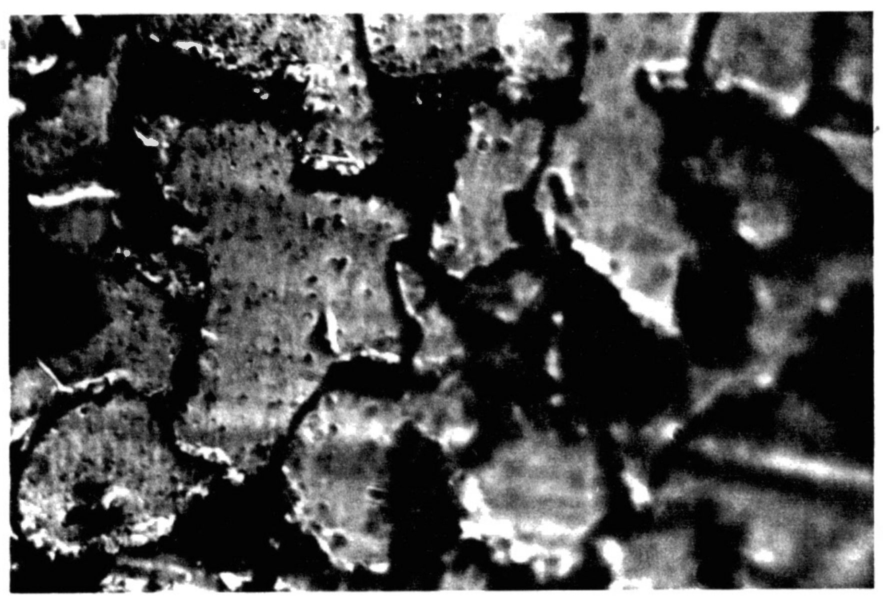
Descriptions of heat straightening or cambering processes applied to various specimens were provided in Table III of Chapter 3. This information was further grouped in Table IV to facilitate comparison of specimens. Most comparisons are made within small differences in data or observation ranges due to the nature of the experiments. All the rates of straightening or cambering were computed by linear regression analysis. The degree of confidence in each observation was expressed in terms of the coefficient of determination (r^2) of each best fit curve in Appendices A through G.

4.3.1 Group I

Figure 17 (a and b) shows the microstructure of the control specimen. The structure is approximately 1/4 ferrite and 3/4 pearlite which, from the phase diagram, indicates about 0.2% of carbon content. The average Rockwell B hardness reading (HRB) of specimen A is 60, as illustrated in Figure 19 in Section 4.3.4. This value correlates well with the Rockwell B hardness value of SAE



a) Specimen A at 150X Magnification



b) Specimen A at 600X Magnification

Figure 17: Microstructures

c) Specimen B at 600X Magnification

d) Specimen D1 at 600X Magnification

Figure 17: Microstructures

e) Specimen D3 at 600X Magnification

f) Specimen G1 at 600X Magnification

Figure 17: Microstructures

1020 which is about 65.7.

The grains of specimen B (Figure 17 c) are slightly elongated as compared with those of specimen A due to bending. While being heat-straightened, the grains were recrystallized, thus regaining original grain size and shape as proven by the microstructures of Specimen D1 (Figure 17 d). The application of force on Specimen D3 (Figure 17 e) and heat cambering on Specimen G1 (Figure 17f) did not change the shape of the recrystallized microstructures.

4.3.2 Group II

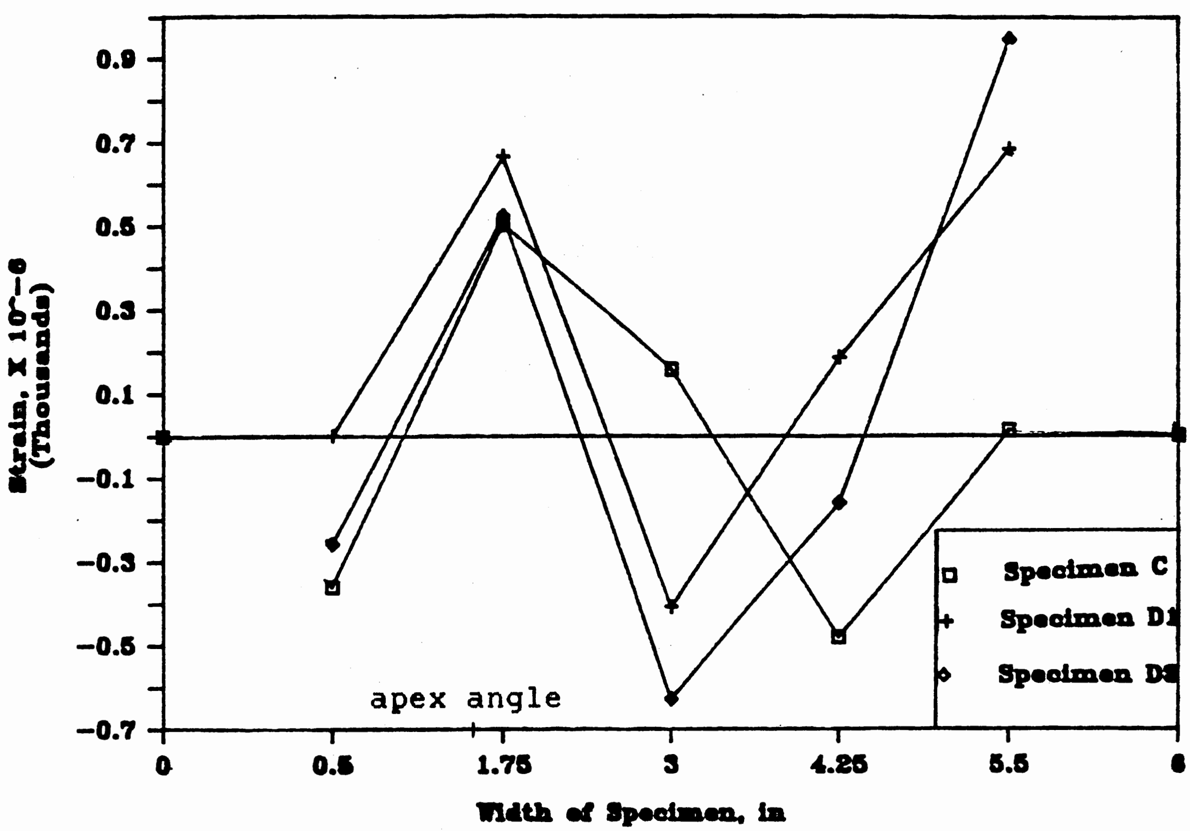
As seen in Appendices A and B, specimen D2 was straightened at the same rate as specimen D1. In specimen D2, expansion in the longitudinal direction was restrained with a bar clamp that exerted about 1100 pounds of force. The axial force was aimed to force expansion in the thickness and in lateral directions. The axial force was not sufficient to bend the specimen while it was yielding. It is concluded that as long as the applied force is below the yielding force of the specimen at the heating temperature, the rate of straightening or cambering is not improved significantly. The same observations was true for specimens E1 and E2.

As shown in Appendices A and F, the rate of straightening was slower than the rate of cambering, 0.0046 inch per heating as opposed to 0.0066 inch per heating. The comparison is made based on data obtained from about twenty heatings after the initiation of the heat straightening or cambering effects. The cambering effect was observed almost instantaneously while the straightening effect was apparent only after about twenty heatings.

4.3.3 Group III

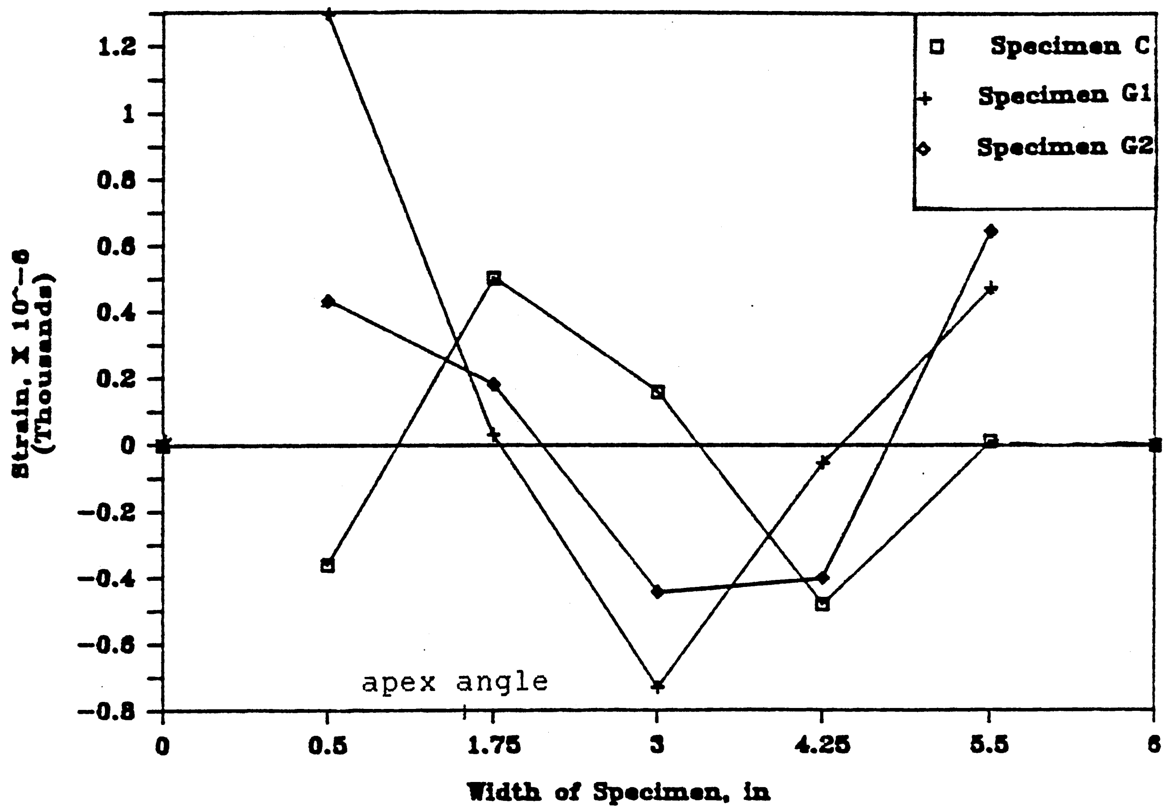
Nonuniform application of heat creates substantial residual stresses as shown in Figure 18. The positive strain regions correspond to compressed regions at the completion of heat straightening or cambering process. The opposite is true for the negative strain region. Thus upsetting or buckling of the specimens will be more profound at the positive strain regions. Figure 18 a) shows that the residual strain or stress pattern of the two heat-straightened specimens (Specimens D1 and D3) are basically the same as that of the force-straightened specimen (Specimen C). The same observation is true for the heat-cambered specimens (Specimens G1 and G2) except at the apex angle region of the vee-heat as illustrated in Figure 18 b). This phenomena can be possibly explained by observing that all regions of the heat-cambered specimens have not undergone prior elongation, thus, the degree of constraints is much higher causing more upsettings especially at the central region. Application of an uniform heat could easily release the residual strains or stresses generated by the straightening or cambering process.

The specimen F2 has yielded and subjected to substantial curvature. Large amount of curvature occurred



a) Heat-Straightened Specimens- D1, D3

Figure 18: Released Strain States



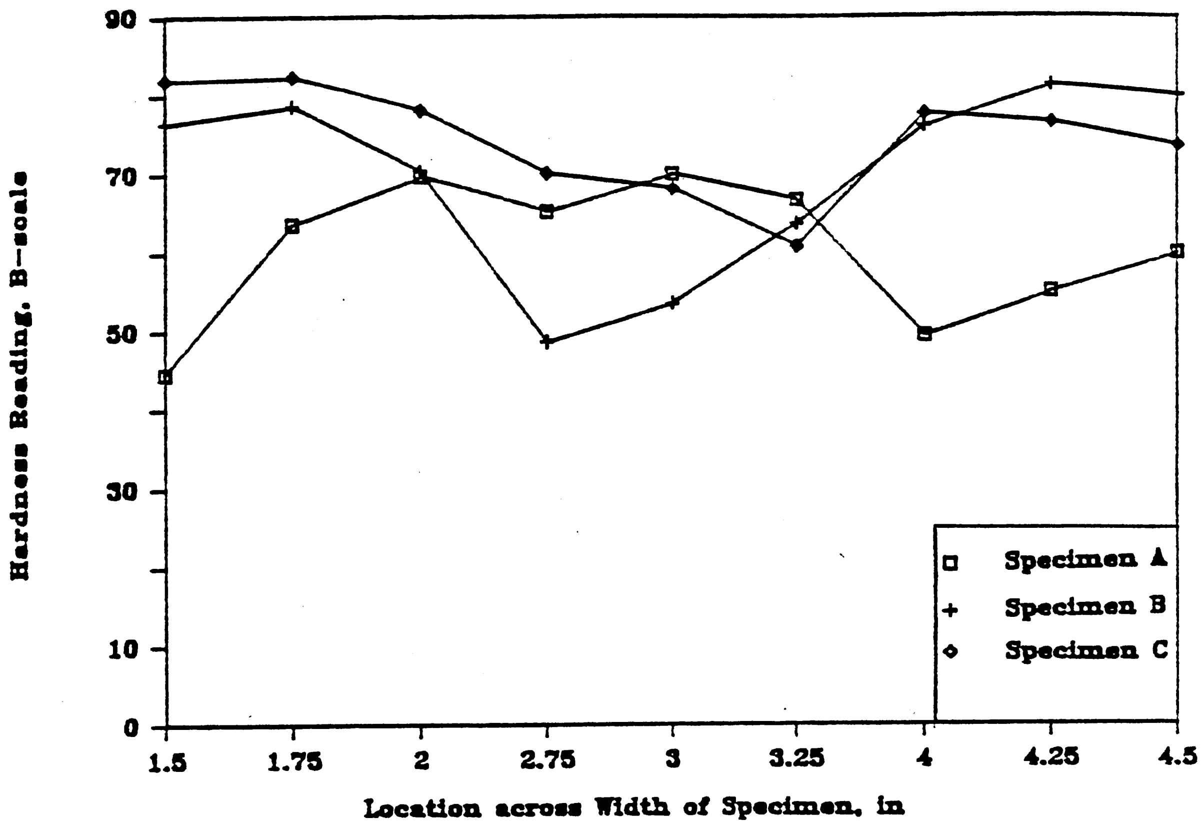
b) Heat-Cambered Specimens- G1, G2

Figure 18: Released Strain States

at the base of the vee-heat due to the fact that this longer edge had undergone more restricted expansion and thus more thermal upsetting. Higher thermal axial stresses at yield point were exerted by the expanding steel which also initiates buckling of the plate. At the same time, the region heated previously began to cool down, attaining higher yield point and producing a greater contracting force at the buckling portion (12). The base of the vee-heat that was compressed resulted in larger permanent change in shape. At this point, the plate buckled towards the heated side of the plate since it shrank more than the unheated side. Some compressive forces still exist at the base of the vee-heat prior to subsequent heating process. If the residual stresses were further released with application of heat, more profound evidence could be observed. At the top of the apex region which was unheated, very little or no grid movement was observed. However, some signs of tension were observed at the middle of the vee-heat region as shown in the enclosed area in Figure 15 b). Thus, a rigid framing system is suggested to prevent buckling of the heated portion that is yielding if the quantity of the contraction force exceeds that required to cause upsetting of the heated material.

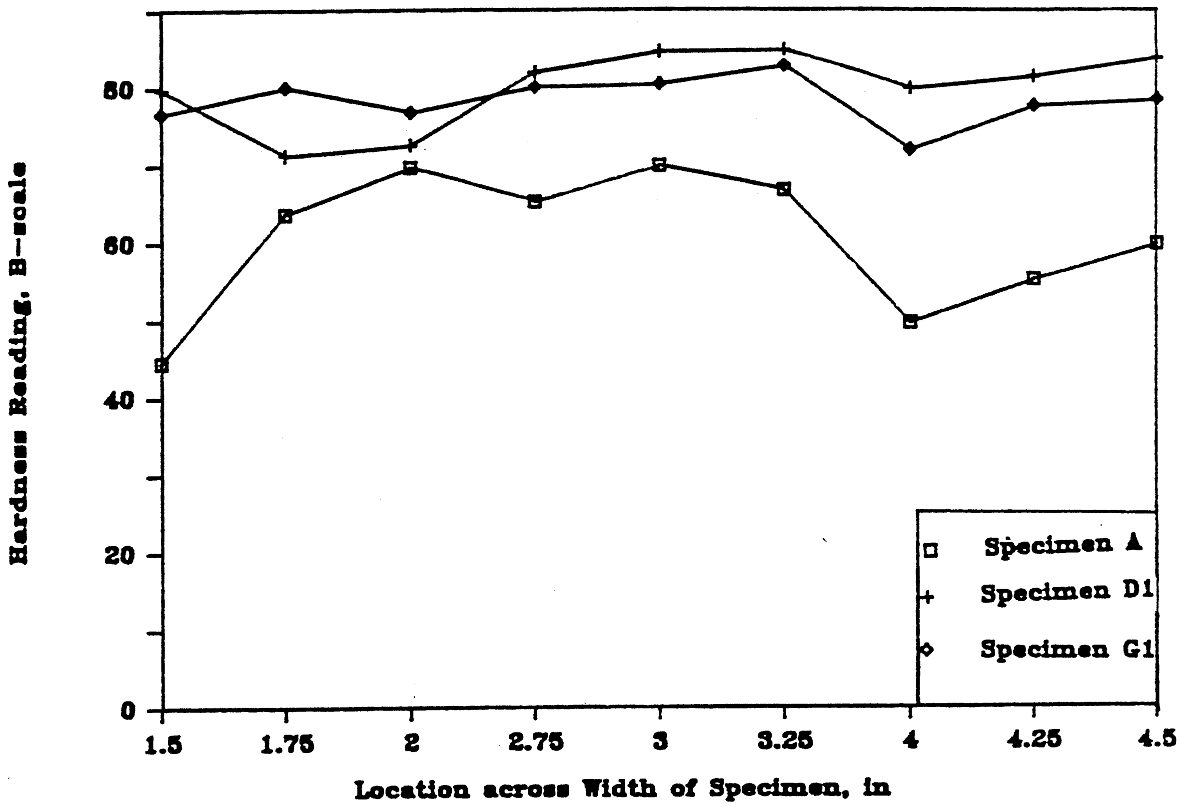
4.3.4 Group IV

A limited number of charpy tests were performed on samples taken from specimens in this group (A, B, C, D1, E2, and G1). At a temperature of $-80^{o}F$, fracture energy was



a) Force-Bent Specimens- B, C

Figure 19: Rockwell Hardness Reading



b) Heat-Straightened (D1) and Heat-Cambered (G1) Specimens

Figure 19: Rockwell Hardness Reading

approximately 5 ft-lbs. This observation reinforces the conclusion that the specimens contain about 0.2% of carbon. The fracture surfaces were typical of brittle fracture without any lateral expansion.

Hardness measurements were made on specimens A, B, C, D1 and G1 using the Rockwell B scale. As seen in Figure 19 (a), specimens B and C, which have undergone mechanical bending, generally yield higher hardness readings than the control specimen when readings are taken from a region approximately one-half inch from the edges. However, for specimen B, the central regions exhibit lower hardness readings. As expected, specimen C, which has undergone the most cold work, yields highest hardness readings. During the mechanical bending process, the central region behaves as a rotating hinge. Thus, it was subjected to less entanglement of dislocations which retard subsequent movements of any other dislocations, including penetration.

From Figure 19 (b), both the heat straightened and cambered specimens yield uniform and higher hardness readings than the standard specimen does. The central regions have been subjected to high compressive stresses, thus, yields higher hardness values.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary and Conclusions

The concept of contraction straightening is more applicable to cambering of a member since the member is basically isolated from prior cold-working. The heat-straightening process takes considerable time unless some auxiliary force can be applied to assist in providing restraint against expansion.

Based on the results of varied types of straightening methods, heating temperatures, and restraint conditions, the following conclusions are reached:

1. Heat straightening involves relief of residual stresses caused by previous cold-working prior to straightening. After recrystallization or release of stress has occurred, the rate of straightening is about the same for all the specimens subjected to the same conditions (Section 4.2).

2. Heat cambering occurs instantaneously and at faster rate than heat straightening does if no extreme amount of residual stress exists in the as-rolled steel sections (Section 4.2 and 4.3.2).

3. Increased depth of vee-heat and application of

mechanical force that is below the yielding strength of the specimen at the heating temperature could supply enough compressive force to resist the residual stresses which oppose the straightening or cambering process. However, both the straightening and cambering rates were not affected substantially. The rate of straightening due to full depth heating can be closely predicted by the shrinkage behavior (Section 4.2).

4. The process of heat straightening or cambering can cause recrystallization of the microstructures if the heating temperature is within 0.3 to 0.6 times the absolute melting temperature in Kelvin (Section 4.3.1). Thus, it can be utilized to refine cold-worked microstructure. However, it is also obvious that heat straightening or cambering can change the material properties of heat-treated materials (Section 4.3.4).

5. Application of external force which is below the yielding force of the specimen at the heating temperature does not improve the rate of straightening or cambering (Section 4.3.2). However, application of extremely high compressive force could initiate buckling of the yielded region (Section 4.3.3).

6. Upsetting and subsequent buckling of the specimens are more profound at the compressed regions. These residual strains or stresses could be released with the application of an uniform heat source (Section 4.3.3).

7. The heating temperature used in the straightening or cambering process should be determined based on the heat

treatment undergone by the specimens.

Based on the findings of this investigation, it is believed that the rate of straightening or cambering can also be increased by inducing a high temperature gradient within the heated area. This can be achieved by heating a specimen in vee-heat pattern as usual, followed by 'vee-cool' with a stream of air at normal temperature. The rate was found to be significantly increased.

5.2 Recommendations for Further Research

During the course of any investigation, questions often arise as a result of the research. Many of the questions are beyond the scope of the study and remain unanswered. The following recommendations would be of practical value toward better understanding and utilization of heat straightening and should be explored.

1. The effect of heat straightening on high-strength steels should be investigated. Presently conflicting property data indicate that problems may be encountered.

2. Study the effects of heat straightening on alloys that have undergone thermomechanical treatment or processing such as isoforming and ausforming processes.

3. Study the cooling methods that can help to maintain high temperature gradients without affecting the microstructure of the heat-straightened specimens.

4. Study methods of preventing buckling of heat-straightened members so as to reduce subsequent stability

failures of the repaired structure.

5. Study the types of deterioration which may occur at the heated area and their long term effects.

6. Further this study in a more comprehensive way especially the recommended 'vee-cool' method.

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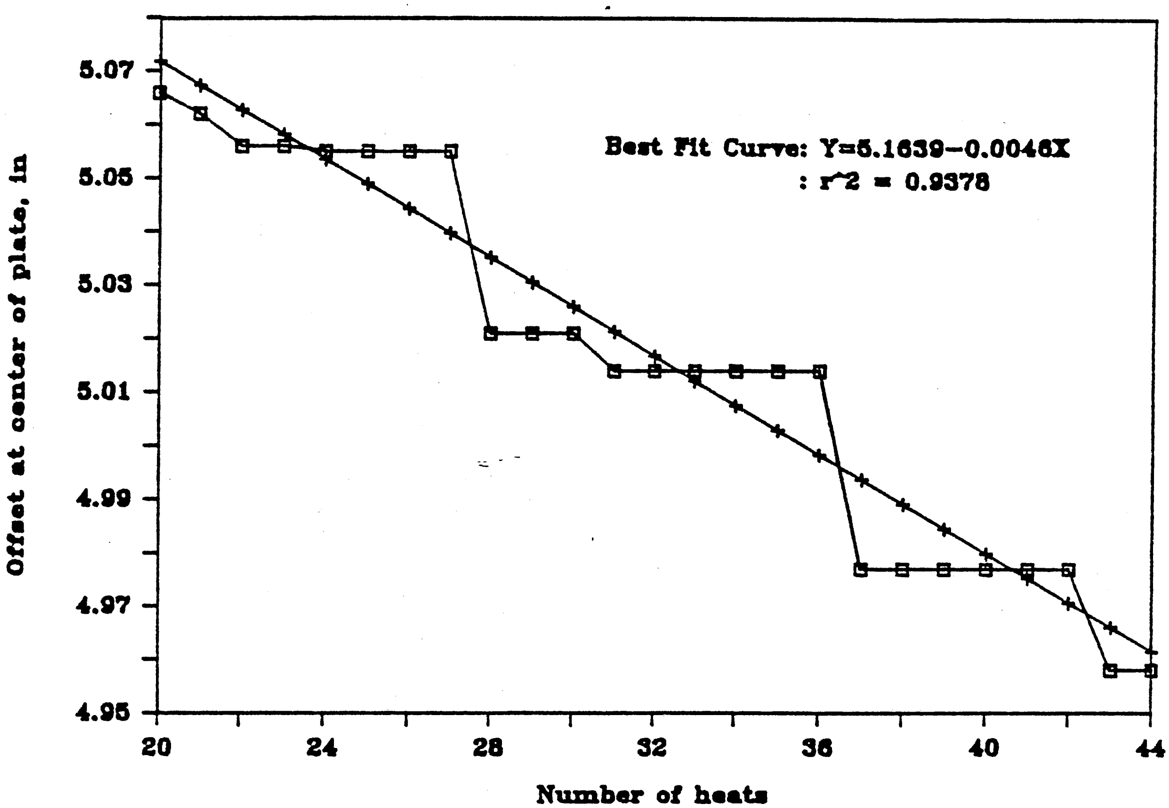
APPENDIX A

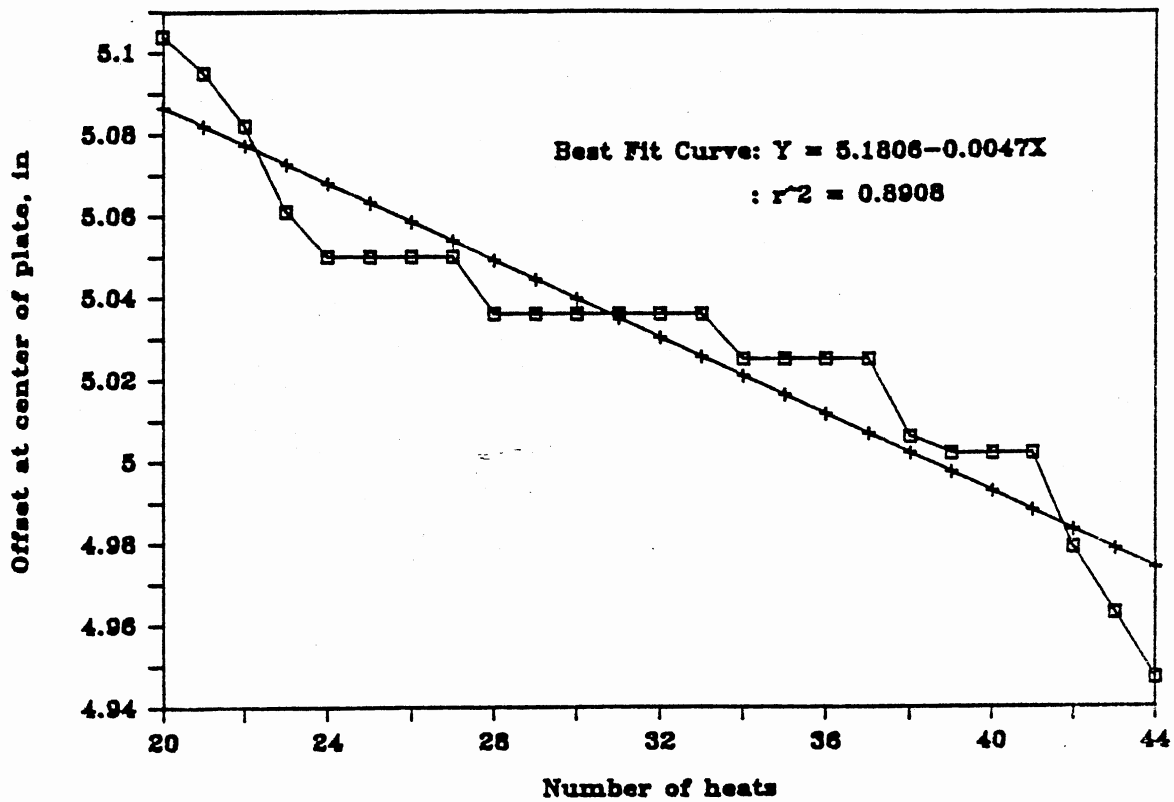
OFFSET AT CENTER OF PLATE D1 VERSUS NUMBER OF

HEATINGS



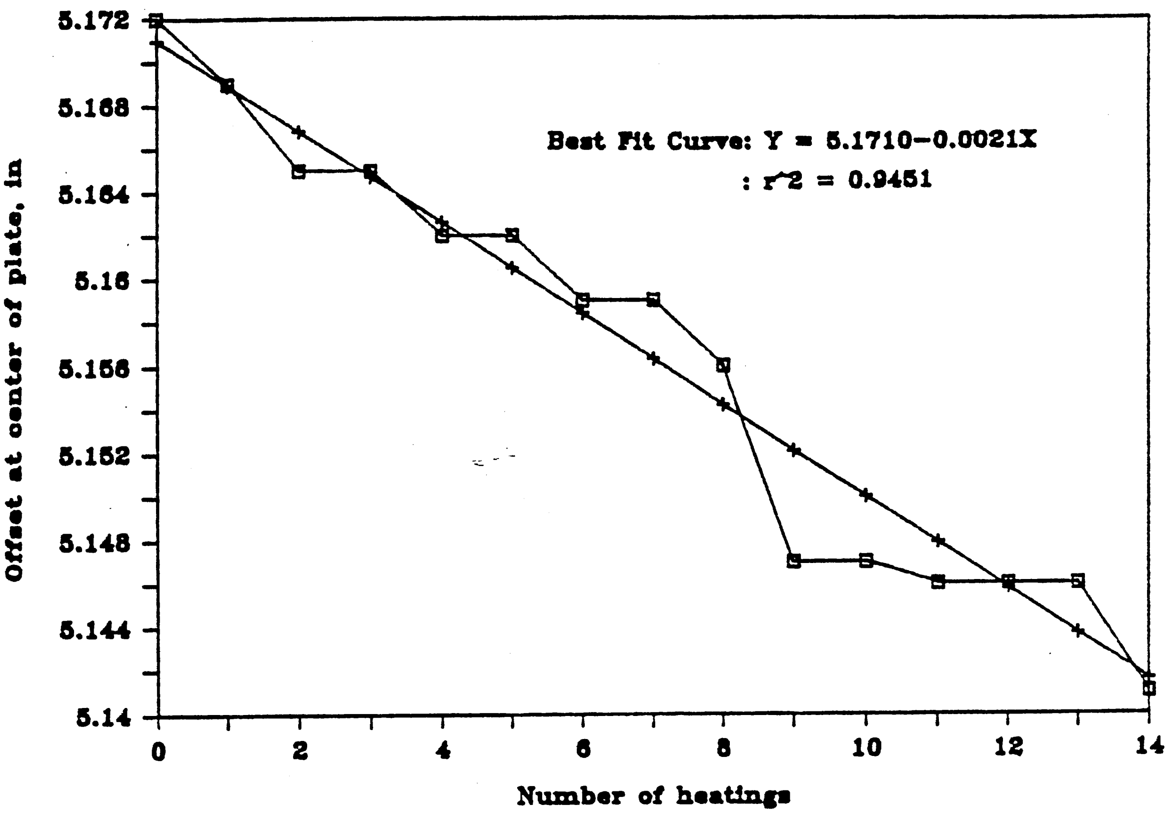
APPENDIX B

OFFSET AT CENTER OF PLATE D2 VERSUS NUMBER OF HEATINGS



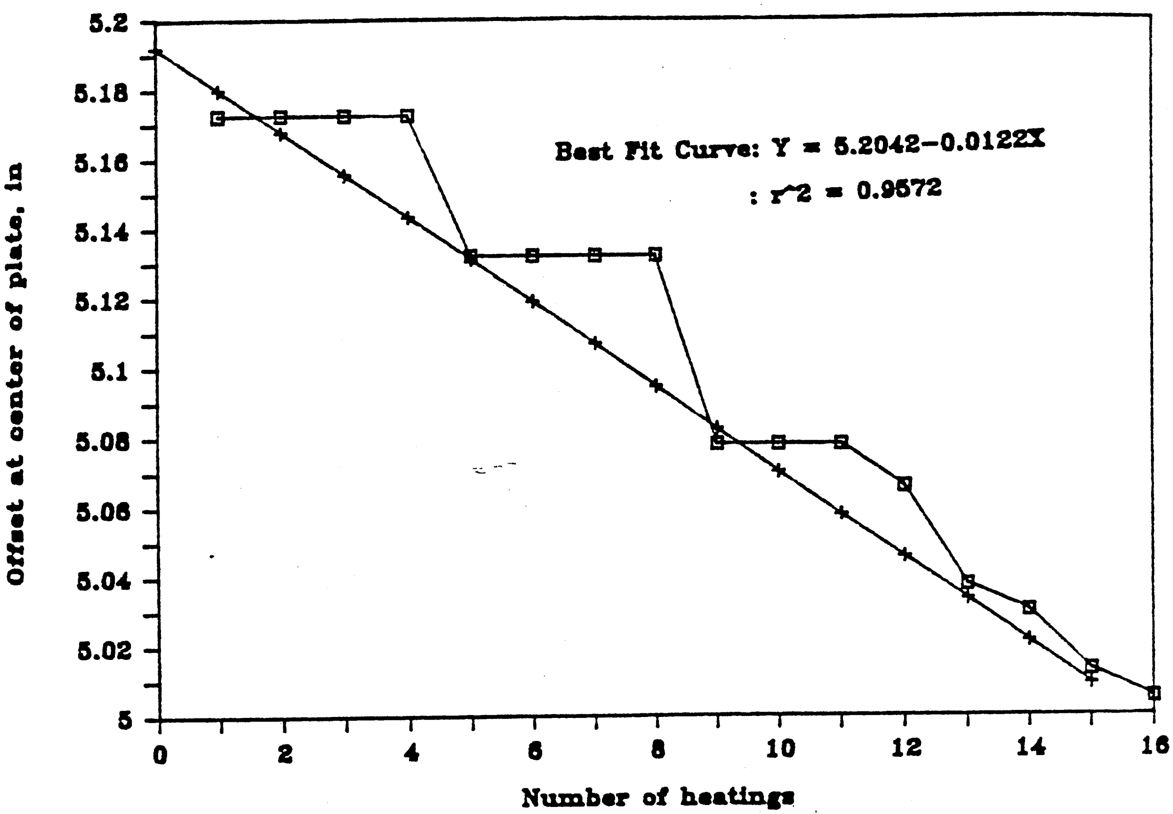
APPENDIX C

OFFSET AT CENTER OF PLATE D3 VERSUS NUMBER OF HEATINGS



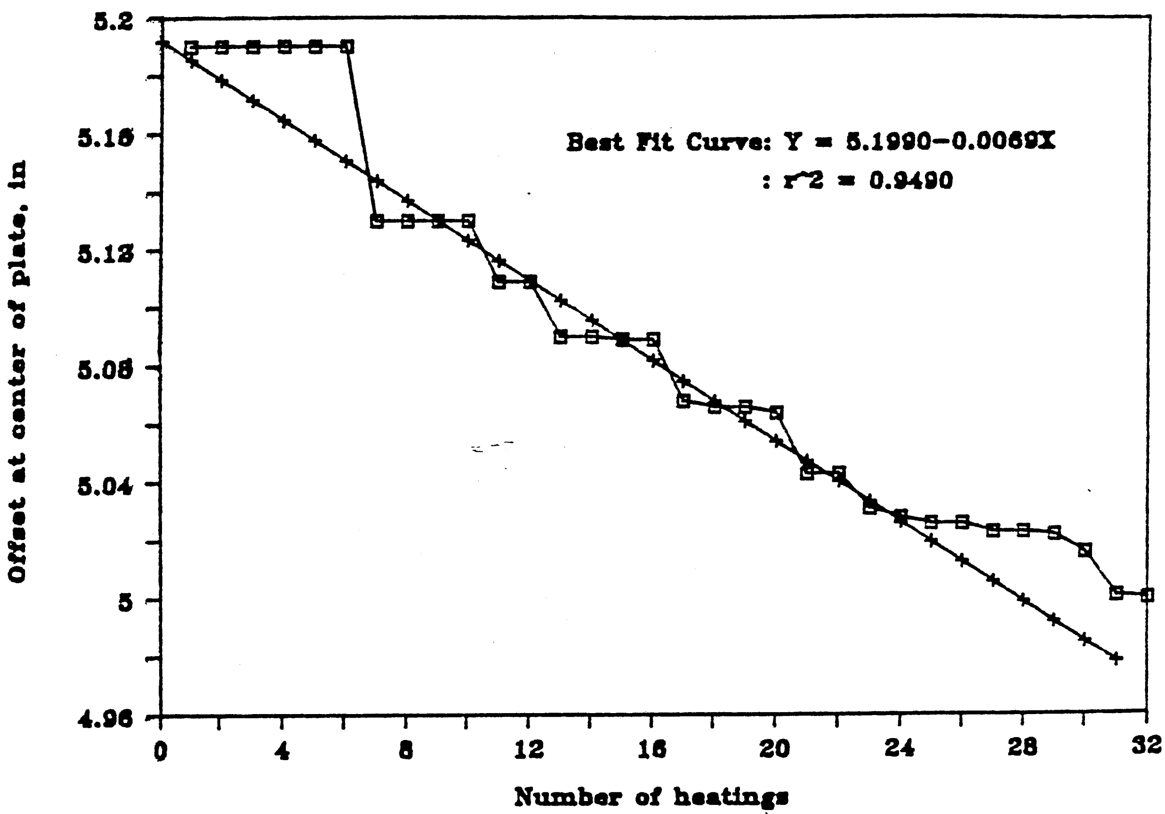
APPENDIX D

OFFSET AT CENTER OF PLATE E1 VERSUS NUMBER OF HEATINGS



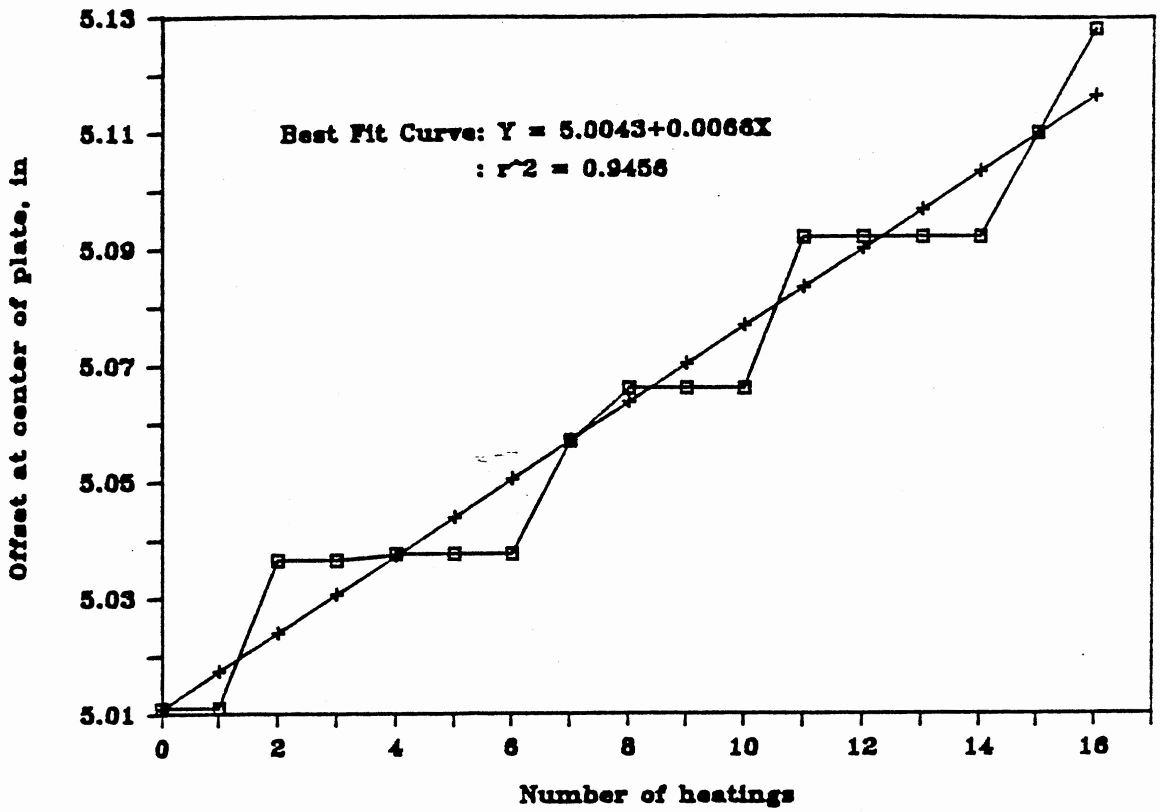
APPENDIX E

OFFSET AT CENTER OF PLATE E2 VERSUS NUMBER OF HEATINGS



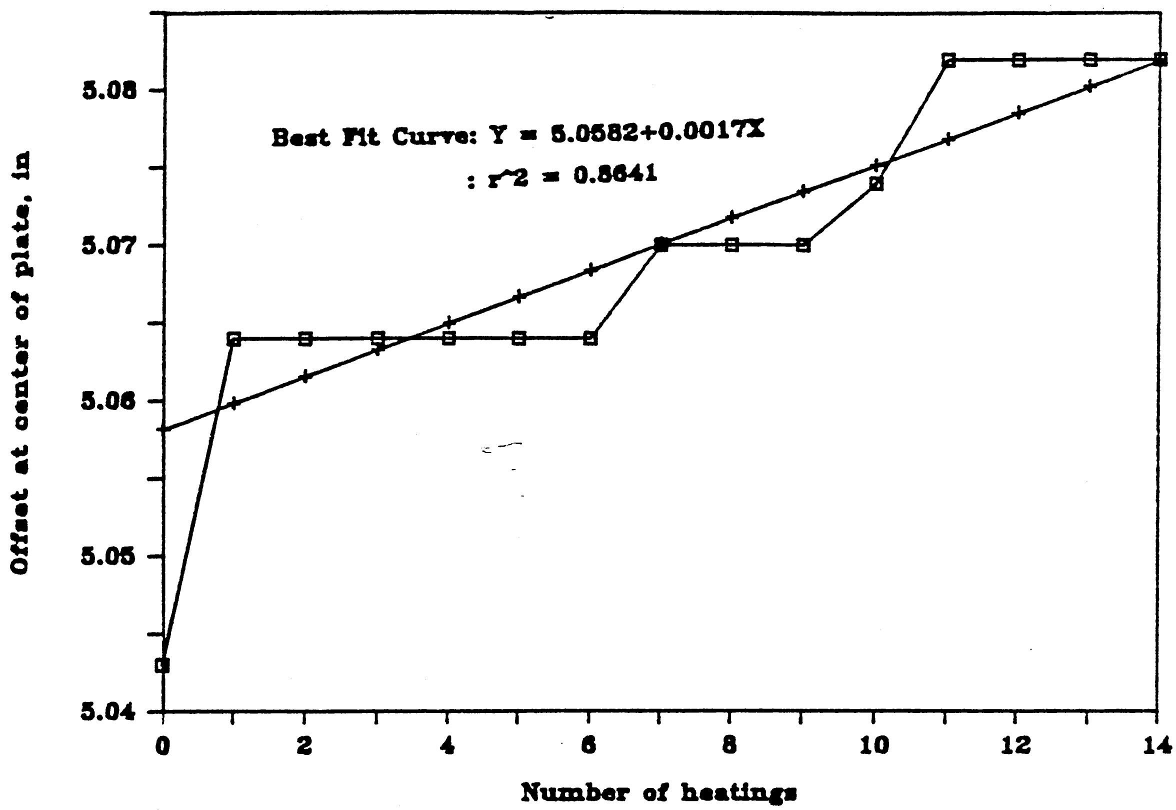
APPENDIX F

OFFSET AT CENTER OF PLATE G1 VERSUS NUMBER OF HEATINGS



APPENDIX G

OFFSET AT CENTER OF PLATE G2 VERSUS NUMBER OF HEATINGS



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